

## 6 Neutrons and Neutron Interactions

A nuclear reactor will not operate without neutrons. Neutrons induce the fission reaction, which produces the heat in CANDU reactors, and fission creates more neutrons. The neutrons produced also engage in other reactions. It is important to know about these neutron interactions.

### 6.1 Neutron Production

Most of the neutrons in a CANDU reactor come directly from fission. About ½% of the neutrons in a reactor at power are emitted as part of fission product decay. These two important types of neutrons, known as prompt and delayed neutrons respectively, are discussed in the next section. The only other important neutron source in a CANDU is the photoneutron reaction.

#### 6.1.1 The Photoneutron Reaction

An energetic gamma ray may interact with a deuterium nucleus, removing a neutron. The deuterium nucleus becomes a normal hydrogen nucleus and the neutron is free to move around.



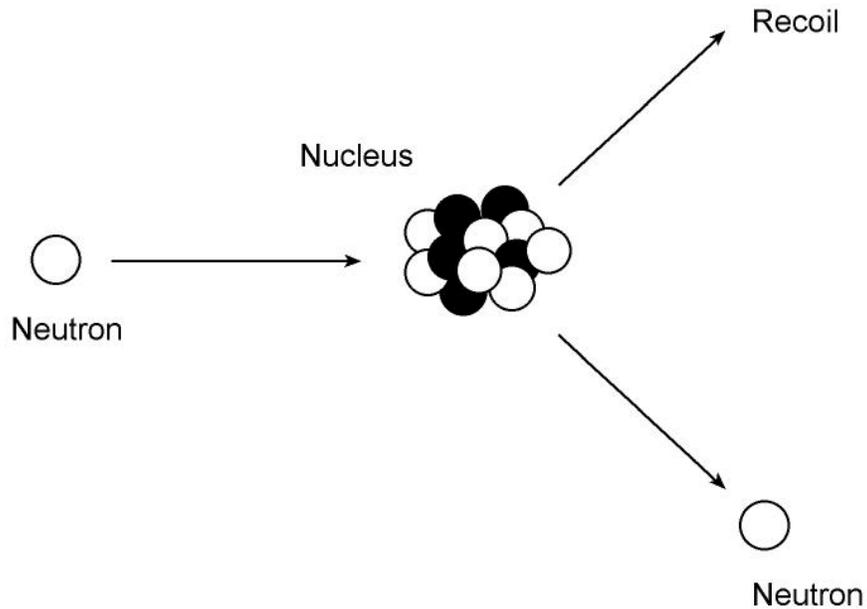
The minimum gamma ray energy for this reaction, 2.22 MeV, is known as the threshold energy. In this example, a gamma ray of energy of 2.22 MeV is absorbed and the total mass increases by 0.00239 u. Looking ahead for a moment, module 6 describes how energy can be converted to mass, and mass to energy. The photoneutron reaction is an example of conversion of energy to mass, as was electron-positron pair production, introduced in module 3. The threshold energy can be equated with the mass difference measured between the initial deuterium atom and the reaction products (the hydrogen atom and neutron) to give the useful mass to energy conversion factor: 1 u = 931.5 MeV.

### 6.2 Neutron Interactions

This section introduces five reactions that can occur when a neutron interacts with a nucleus. In the first two, known as scattering reactions, a neutron emerges from the reaction. In the remaining reactions, known as absorption reactions, the neutron is absorbed into the nucleus and something different emerges.

### 6.3 Elastic Scattering—(n, n)

Elastic scattering resembles a billiard ball collision. A neutron collides with a nucleus, transfers some energy to it, and bounces off in a different direction. (Sometimes it absorbs the neutron and then re-emits it, conserving kinetic energy.) The fraction of its initial energy lost depends on whether it hits the target nucleus dead-on or at an angle—exactly like the cue ball striking a ball on the billiard table. The target nucleus gains the energy lost by the neutron, and then moves at an increased speed.



**Figure 6.1**  
**Elastic Scattering**

Light nuclei are the most effective for slowing neutrons. A neutron colliding with a heavy nucleus rebounds with little loss of speed and transfers very little energy—rather like firing the cue ball at a cannon ball. On the other hand, neutrons will not be scattered by the light electron clouds surrounding the nucleus, but will travel straight on—much like baseballs through a fog.

### 6.4 Inelastic Scattering—(n, n $\gamma$ )

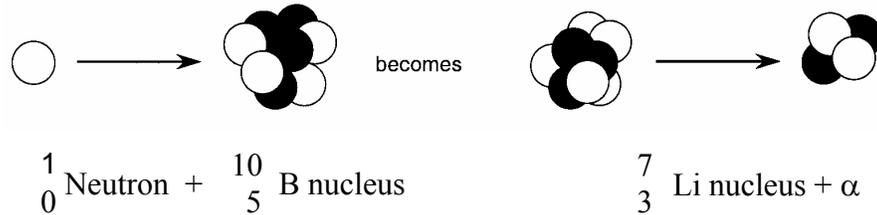
A neutron may strike a nucleus and be temporarily absorbed, forming a compound nucleus. This will be in an excited state. It may de-excite by emitting another neutron of lower energy, together with a gamma photon, which takes the remaining energy. This process is called inelastic scattering. It generally happens only when high-energy



more important, it also emits very penetrating, high-energy gamma rays.

### 6.5.2 Neutron-Alpha Reaction (n, α)

Neutrons captured by boron-10 cause the following reaction:

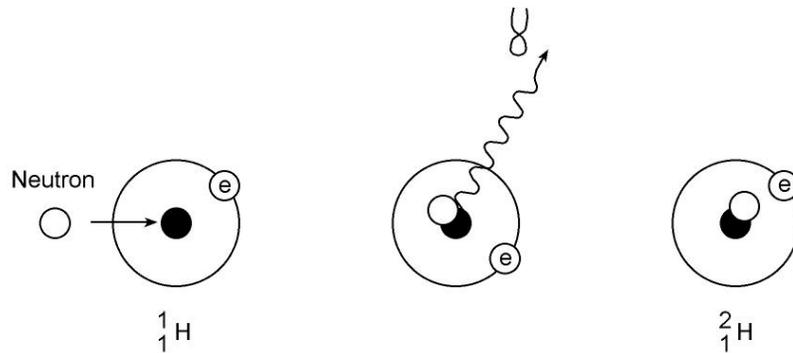


### 6.6 Radiative Capture—(n, γ)

This is the most common nuclear reaction. The compound nucleus formed emits only a gamma photon. In other words, the product nucleus is an isotope of the same element as the original nucleus. Its mass number increases by one.

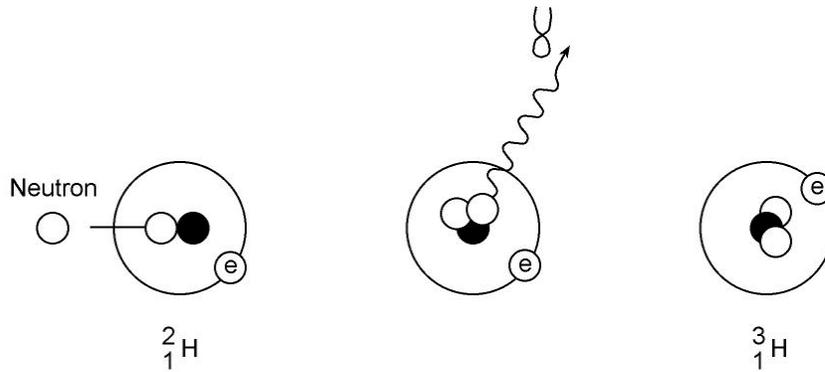
#### Examples

The simplest radiative capture occurs when hydrogen absorbs a neutron to produce deuterium (heavy Hydrogen);



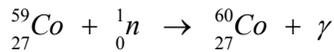
The deuterium formed is a stable nuclide. However, many radiative capture products are radioactive and are beta-gamma emitters.

Deuterium itself undergoes a radiative capture reaction to form tritium;



The tritium isotope is unstable and is a major radiation hazard in CANDU reactors.

Stable cobalt-59 undergoes radiative capture to form highly radioactive Co-60:



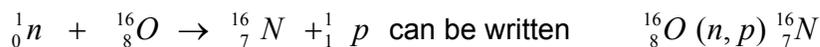
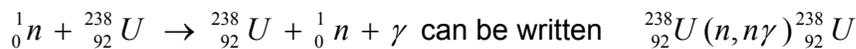
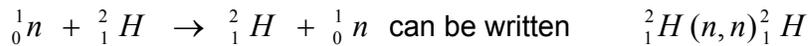
Cobalt-60 has a long half-life (5¼ years) and emits very penetrating gamma radiation when it decays, making it a serious hazard among activated corrosion products. Normal steel usually contains a small amount of cobalt, but the concentration in reactor grade materials is limited to reduce the radiation hazard.

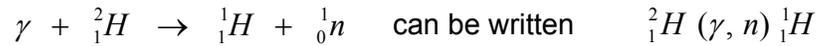
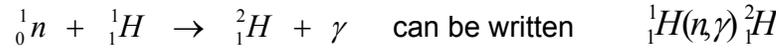
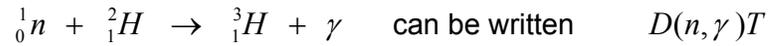
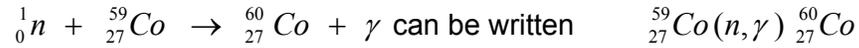
Cobalt-60 is an isotope commonly used in radiation treatment of cancer.

## 6.7 Fission

This most important reaction is the subject of the next lesson.

The five neutron reactions introduced in this section are of two types: scattering reactions (the first two), and absorption reactions (the others). The following examples illustrate a convenient shorthand notation for these reactions.



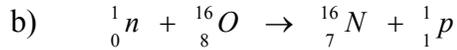
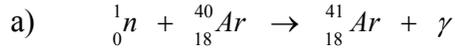


### 6.8 Summary of Key Ideas

- Important sources of neutrons in the reactor are fission, delayed neutrons and photoneutrons.
- Photoneutrons are released from nuclei when a high energy gamma interacts with a nucleus and releases a neutron.
- The most important photoneutron reaction in a CANDU reactor is photoneutron released from a deuterium nucleus by a gamma ray with an energy greater than 2.2 MeV.
- Neutrons may be scattered by elastic and inelastic scattering.
- Neutrons also cause transmutation reactions. A transmutation occurs when a neutron is absorbed by a nucleus and some other particle is emitted.
- (n,  $\gamma$ ), (n, p), (n,  $\alpha$ ) are among the common transmutation reactions.

**6.9 Assignment**

1. Write the equation for the photo-neutron reaction with H-2.
2. Describe elastic and inelastic scattering of neutrons.
3. Identify the following reactions:



4. List the examples of neutron reactions in this chapter that are also activations.
5. Complete the following equations and name the reaction. (The atomic numbers are 6 for carbon, 7 for nitrogen, and 8 for oxygen.)
  - a) C-13 (n,  $\gamma$ ) ?
  - b) O-17 (n, p) ?
  - c) O-17 (n,  $\alpha$ ) ?
  - d) N-14 (n, p) ?

6. Complete the following table:

Name of Reaction	Reaction type (n,x)	Target Nucleus	Product Nucleus
?	(n, $\gamma$ )	${}_1^2H$	?
Transmutation	(n, p)	?	${}_7^{16}N$
Radiative Capture	?	${}_8^{18}O$	?
?	(n, ?)	${}_6^{12}C$	${}_6^{13}C$