NUCLEAR FISSION

Nuclear fission is a process in which an atom splits and releases energy, fission products, and neutrons. The neutrons released by fission can, in turn, cause the fission of other atoms.

EO 4.1 **EXPLAIN the fission process using the liquid drop model of a nucleus.**

EO 4.2 **DEFINE the following terms:**

- **a. Excitation energy (E_{exc})**
- **b. Critical energy (E_{crit})**

EO 4.3 **DEFINE the following terms:**

- **a. Fissile material**
- **b. Fissionable material**
- **c. Fertile material**

EO 4.4 **DESCRIBE the processes of transmutation, conversion, and breeding.**

EO 4.5 **DESCRIBE the curve of Binding Energy per Nucleon versus mass number and give a qualitative description of the reasons for its shape.**

EO 4.6 **EXPLAIN why only the heaviest nuclei are easily fissioned.**

EO 4.7 **EXPLAIN why uranium-235 fissions with thermal neutrons and uranium-238 fissions only with fast neutrons.**

Fission

In the fission reaction the incident neutron enters the heavy target nucleus, forming a compound nucleus that is excited to such a high energy level ($E_{exc} > E_{crit}$) that the nucleus "splits" (fissions) into two large fragments plus some neutrons. An example of a typical fission reaction is shown below.

$$ {}^{1}_{0}\text{n} + {}^{235}_{92}\text{U} \rightarrow \left({}^{236}_{92}\text{U} \right)^{*} \rightarrow {}^{140}_{55}\text{Cs} + {}^{93}_{37}\text{Rb} + 3 \left({}^{1}_{0}\text{n} \right) $$

A large amount of energy is released in the form of radiation and fragment kinetic energy.

Liquid Drop Model of a Nucleus

The nucleus is held together by the attractive nuclear force between nucleons, which was discussed in a previous chapter. The characteristics of the nuclear force are listed below.

(a) very short range, with essentially no effect beyond nuclear dimensions (~10^{-13} cm)

(b) stronger than the repulsive electrostatic forces within the nucleus

(c) independent of nucleon pairing, in that the attractive forces between pairs of neutrons are no different than those between pairs of protons or a neutron and a proton

(d) saturable, that is, a nucleon can attract only a few of its nearest neighbors

One theory of fission considers the fissioning of a nucleus similar in some respects to the splitting of a liquid drop. This analogy is justifiable to some extent by the fact that a liquid drop is held together by molecular forces that tend to make the drop spherical in shape and that try to resist any deformation in the same manner as nuclear forces are assumed to hold the nucleus together. By considering the nucleus as a liquid drop, the fission process can be described.

Referring to Figure 18(A), the nucleus in the ground state is undistorted, and its attractive nuclear forces are greater than the repulsive electrostatic forces between the protons within the nucleus. When an incident particle (in this instance a neutron) is absorbed by the target nucleus, a compound nucleus is formed. The compound nucleus temporarily contains all the charge and mass involved in the reaction and exists in an excited state. The excitation energy added to the compound nucleus is equal to the binding energy contributed by the incident particle plus the kinetic energy possessed by that particle. Figure 18(B) illustrates the excitation energy thus imparted to the compound nucleus, which may cause it to oscillate and become distorted. If the excitation energy is greater than a certain critical energy, the oscillations may cause the compound nucleus to become dumbbell-shaped. When this happens, the attractive nuclear forces (short-range) in the neck area are small due to saturation, while the repulsive electrostatic forces (long-range) are only slightly less than before. When the repulsive electrostatic forces exceed the attractive nuclear forces, nuclear fission occurs, as illustrated in Figure 18(C).

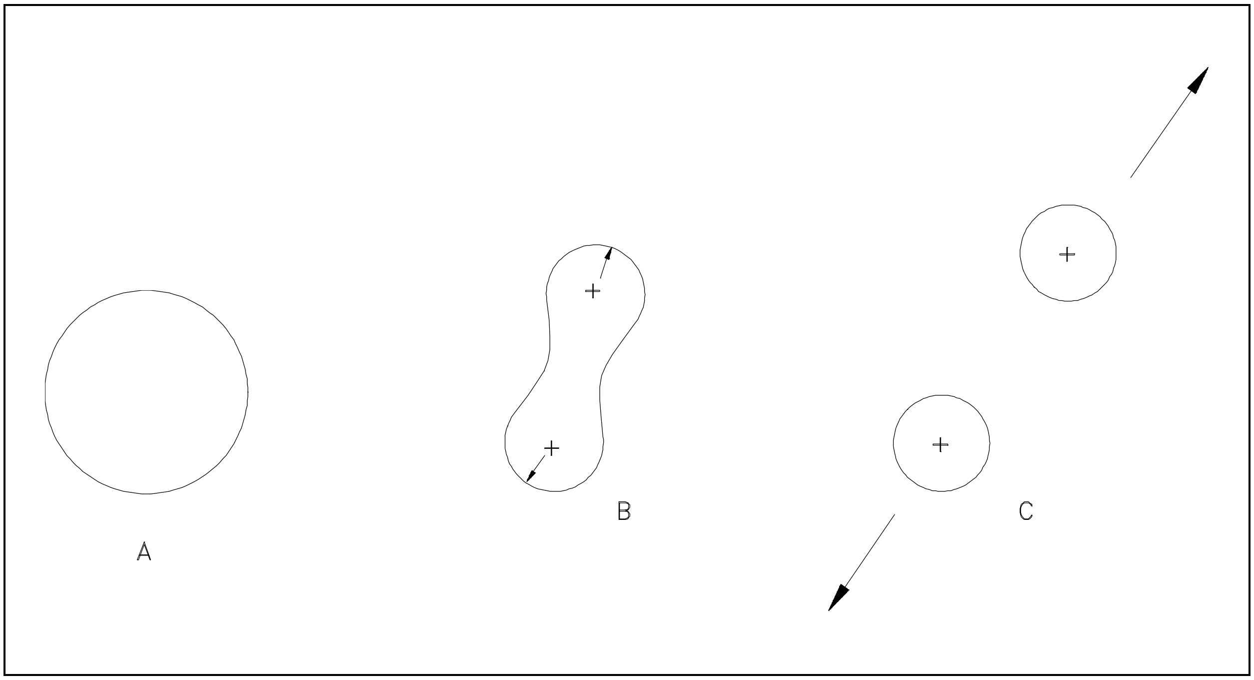

Figure 18 Liquid Drop Model of Fission

Critical Energy

The measure of how far the energy level of a nucleus is above its ground state is called the *excitation energy* (E_{exc}). For fission to occur, the excitation energy must be above a particular value for that nuclide. The *critical energy* (E_{crit}) is the minimum excitation energy required for fission to occur.

Fissile Material

A *fissile material* is composed of nuclides for which fission is possible with neutrons of any energy level. What is especially significant about these nuclides is their ability to be fissioned with zero kinetic energy neutrons (thermal neutrons). Thermal neutrons have very low kinetic energy levels (essentially zero) because they are roughly in equilibrium with the thermal motion of surrounding materials. Therefore, in order to be classified as fissile, a material must be capable of fissioning after absorbing a thermal neutron. Consequently, they impart essentially no kinetic energy to the reaction. Fission is possible in these materials with thermal neutrons, since the change in binding energy supplied by the neutron addition alone is high enough to exceed the critical energy. Some examples of fissile nuclides are uranium-235, uranium-233, and plutonium-239.

Fissionable Material

A *fissionable material* is composed of nuclides for which fission with neutrons is possible. All fissile nuclides fall into this category. However, also included are those nuclides that can be fissioned only with high energy neutrons. The change in binding energy that occurs as the result of neutron absorption results in a nuclear excitation energy level that is less than the required critical energy. Therefore, the additional excitation energy must be supplied by the kinetic energy of the incident neutron. The reason for this difference between fissile and fissionable materials is the so-called odd-even effect for nuclei. It has been observed that nuclei with even numbers of neutrons and/or protons are more stable than those with odd numbers. Therefore, adding a neutron to change a nucleus with an odd number of neutrons to a nucleus with an even number of neutrons produces an appreciably higher binding energy than adding a neutron to a nucleus already possessing an even number of neutrons. Some examples of nuclides requiring high energy neutrons to cause fission are thorium-232, uranium-238, and plutonium-240. Table 4 indicates the critical energy (E_{crit}) and the binding energy change for an added neutron (BE_n) to target nuclei of interest. For fission to be possible, the change in binding energy plus the kinetic energy must equal or exceed the critical energy ($\Delta BE + KE \geq E_{crit}$).

TABLE 4
Critical Energies Compared to Binding Energy of Last Neutron

Target Nucleus	Critical Energy E_{crit}	Binding Energy of Last Neutron BE_n	$BE_n - E_{crit}$
$^{232}_{90}Th$	7.5 MeV	5.4 MeV	-2.1 MeV
$^{238}_{92}U$	7.0 MeV	5.5 MeV	-1.5 MeV
$^{235}_{92}U$	6.5 MeV	6.8 MeV	+0.3 MeV
$^{233}_{92}U$	6.0 MeV	7.0 MeV	+1.0 MeV
$^{239}_{94}Pu$	5.0 MeV	6.6 MeV	+1.6 MeV

Uranium-235 fissions with thermal neutrons because the binding energy released by the absorption of a neutron is greater than the critical energy for fission; therefore uranium-235 is a fissile material. The binding energy released by uranium-238 absorbing a thermal neutron is less than the critical energy, so additional energy must be possessed by the neutron for fission to be possible. Consequently, uranium-238 is a fissionable material.

Fertile Material

All of the neutron absorption reactions that do not result in fission lead to the production of new nuclides through the process known as *transmutation*. These nuclides can, in turn, be transmuted again or may undergo radioactive decay to produce still different nuclides. The nuclides that are produced by this process are referred to as transmutation products. Because several of the fissile nuclides do not exist in nature, they can only be produced by nuclear reactions (transmutation). The target nuclei for such reactions are said to be fertile. *Fertile materials* are materials that can undergo transmutation to become fissile materials. Figure 19 traces the transmutation mechanism by which two fertile nuclides, thorium-232 and uranium-238, produce uranium-233 and plutonium-239, respectively.

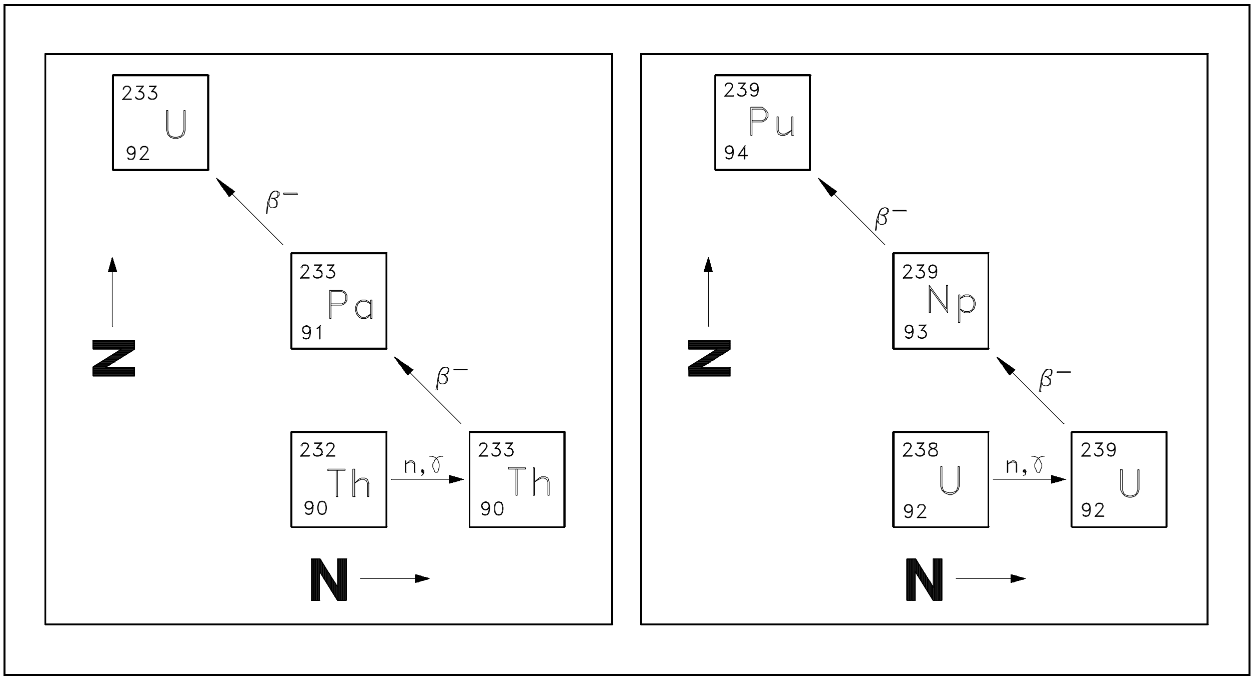

Figure 19 Conversion of Fertile Nuclides to Fissile Nuclides

If a reactor contains fertile material in addition to its fissile fuel, some new fuel will be produced as the original fuel is burned up. This is called *conversion*. Reactors that are specifically designed to produce fissionable fuel are called "breeder" reactors. In such reactors, the amount of fissionable fuel produced is greater than the amount of fuel burnup. If less fuel is produced than used, the process is called conversion, and the reactor is termed a "converter."

Binding Energy Per Nucleon (BE/A)

As the number of particles in a nucleus increases, the total binding energy also increases. The rate of increase, however, is not uniform. This lack of uniformity results in a variation in the amount of binding energy associated with each nucleon within the nucleus. This variation in the binding energy per nucleon (BE/A) is easily seen when the average BE/A is plotted versus atomic mass number (A), as shown in Figure 20.

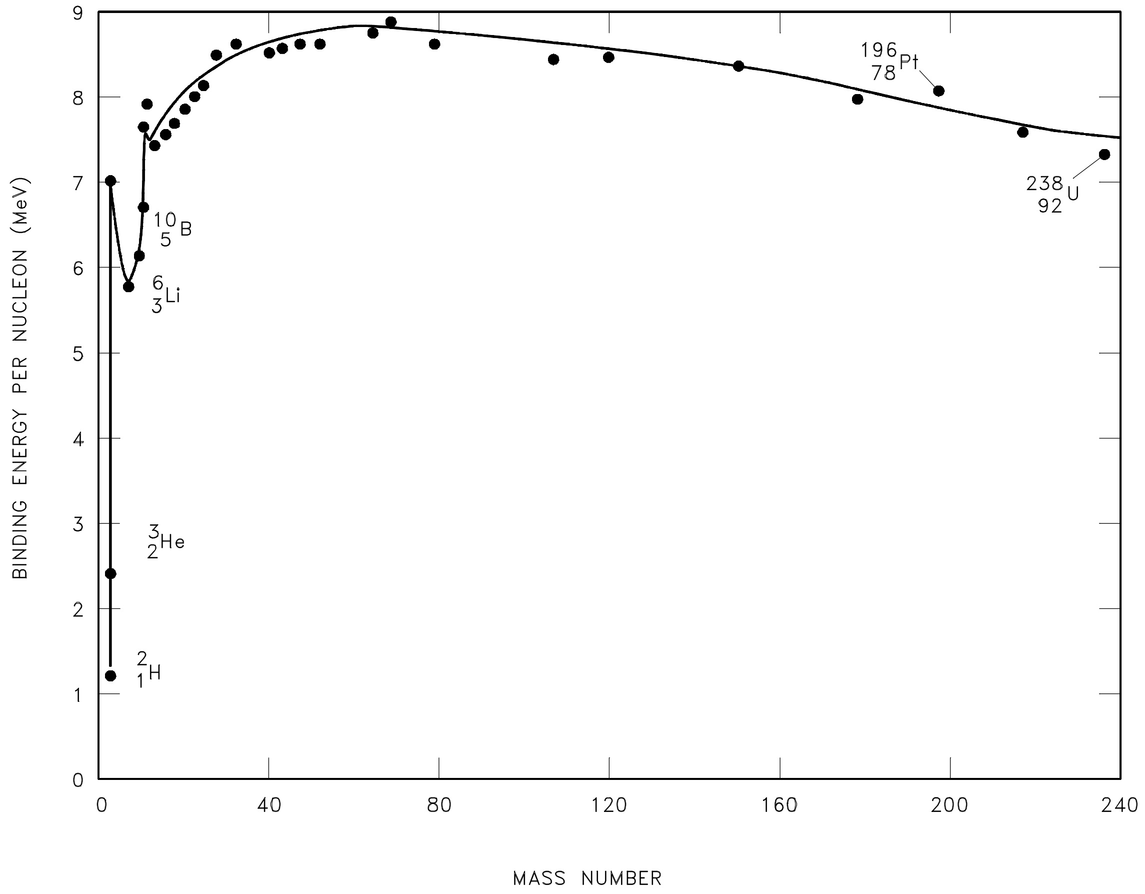

Figure 20 Binding Energy per Nucleon vs. Mass Number

Figure 20 illustrates that as the atomic mass number increases, the binding energy per nucleon decreases for A > 60. The BE/A curve reaches a maximum value of 8.79 MeV at A = 56 and decreases to about 7.6 MeV for A = 238. The general shape of the BE/A curve can be explained using the general properties of nuclear forces. The nucleus is held together by very short-range attractive forces that exist between nucleons. On the other hand, the nucleus is being forced apart by long range repulsive electrostatic (coulomb) forces that exist between all the protons in the nucleus.

As the atomic number and the atomic mass number increase, the repulsive electrostatic forces within the nucleus increase due to the greater number of protons in the heavy elements. To overcome this increased repulsion, the proportion of neutrons in the nucleus must increase to maintain stability. This increase in the neutron-to-proton ratio only partially compensates for the growing proton-proton repulsive force in the heavier, naturally occurring elements. Because the repulsive forces are increasing, less energy must be supplied, on the average, to remove a nucleon from the nucleus. The BE/A has decreased. The BE/A of a nucleus is an indication of its degree of stability. Generally, the more stable nuclides have higher BE/A than the less stable ones. The increase in the BE/A as the atomic mass number decreases from 260 to 60 is the primary reason for the energy liberation in the fission process. In addition, the increase in the BE/A as the atomic mass number increases from 1 to 60 is the reason for the energy liberation in the fusion process, which is the opposite reaction of fission.

The heaviest nuclei require only a small distortion from a spherical shape (small energy addition) for the relatively large coulomb forces forcing the two halves of the nucleus apart to overcome the attractive nuclear forces holding the two halves together. Consequently, the heaviest nuclei are easily fissionable compared to lighter nuclei.

Summary

The important information in this chapter is summarized on the following page.

Nuclear Fission Summary

- The fission process can be explained using the liquid drop model of a nucleus. In the ground state the nucleus is nearly spherical in shape. After the absorption of a neutron, the nucleus will be in an excited state and start to oscillate and become distorted. If the oscillations cause the nucleus to become shaped like a dumbbell, the repulsive electrostatic forces will overcome the short-range attractive nuclear forces, and the nucleus will split in two.

- Excitation energy is the amount of energy a nucleus has above its ground state.

- Critical energy is the minimum excitation energy that a nucleus must have before it can fission.

- Fissile material is material for which fission is possible with neutrons that have zero kinetic energy. Fissionable material is material for which fission caused by neutron absorption is possible provided the kinetic energy added with the binding energy is greater than the critical energy. Fertile material is material that can undergo transmutation to become fissile material.

- Transmutation is the process of neutron absorption and subsequent decay, which changes one nuclide to another nuclide. Conversion is the process of transmuting fertile material into fissile material in a reactor, where the amount of fissile material produced is less than the amount of fissile material consumed. Breeding is the same as conversion, except the amount of fissile material produced is more than the amount of fissile material consumed.

- The curve of binding energy per nucleon increases quickly through the light nuclides and reaches a maximum at a mass number of about 56. The curve decreases slowly for mass numbers greater than 60.

- The heaviest nuclei are easily fissionable because they require only a small distortion from the spherical shape to allow the coulomb forces to overcoming the attractive nuclear force, forcing the two halves of the nucleus apart.

- Uranium-235 fissions with thermal neutrons because the binding energy released by the absorption of a neutron is greater than the critical energy for fission. The binding energy released by uranium-238 absorbing a neutron is less than the critical energy, so additional kinetic energy must be possessed by the neutron for fission to be possible.