11.6: Nuclear Fission

The process by which nitrogen is converted to carbon-14 is an example of *neutron capture*, in which particles are absorbed by the nucleus of another atom to form a new element. These types of reactions are actually quite common in nuclear chemistry. A uranium-235 nucleus captures a “slow-moving” neutron, just like nitrogen captures a neutron, leading to the formation of carbon-14. Initially, uranium-236 is formed, but this nucleus has a neutron-to-proton ratio that makes it exceptionally unstable. The unstable nucleus instantaneously breaks apart (undergoes **fission**) to form lighter elements and to release additional free neutrons. As the nucleus breaks apart, a significant amount of energy is also released. A nuclear equation showing a typical fission of uranium-235 is shown below:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$$

The three neutrons that are released are now speeding through the mass of uranium. If these are captured by another nucleus, the process happens again and three more neutrons are released. This represents a *chain reaction*, and in order to sustain a chain reaction like this, the mass or uranium must be large enough so that the probability of every released neutron being captured by another uranium is high. The mass of uranium (or other fissile element) that is required in order to sustain a chain reaction is called the **critical mass**.

The process of nuclear fission is best known within the context of fission bombs and as the process that operates within nuclear power plants. Designing a workable fission bomb presents many technical challenges. A mass of fissile material that exceeds the critical mass is unstable, so you must begin with a smaller, non-critical mass and somehow create one within a few microseconds. In the original design, this was accomplished by taking two non-critical pieces and forcing them together (very rapidly). This is typically referred to as a “gun assembly”, in which one piece of fissile uranium is fired at a fissile uranium target at the end of the weapon, similar to firing a bullet down a gun barrel.

Each of the uranium fragments are less than a critical mass, but when they collide, they form a mass capable of sustaining the nuclear chain reaction. The assembly stays together for a few microseconds before the energy released from the fission blows it to pieces. The trick is designing nuclear devices like this is to keep them together long enough so that enough energy is released. Neutron reflectors and “boosters” are generally used to accomplish this, nonetheless, this basic type of weapon is inefficient, although easy to design and incredibly deadly. A critical mass of uranium-235 is a sphere that is slightly less than 7 inches in diameter.

A much more efficient fission bomb is based on achieving a critical mass of fissile material, not by combining smaller fragments, but by increasing the density of a sub-critical mass to the point that the rate of neutron capture sustains the chain reaction. This design is called the “implosion” bomb and it basically consists of a sphere of fissile material surrounded by shaped explosives that must be detonated simultaneously. The resulting shock wave compresses the fissile material, allowing the chain reaction to occur. This type of design requires much less fissile material, but is technically challenging. Modern devices have neutron reflectors, “neutron initiators”, etc., and sophisticated bombs can be efficient, have a high yield and a relatively small physical size.

In a nuclear reactor designed to heat water, produce steam and electrical power, the chemistry is the same, but *control rods* are introduced between the pieces of fissile material to absorb some of the neutrons that are produced so that a critical mass is never achieved and the chain reaction can be controlled. In this set-up, as the control rods are withdrawn, the chain reaction speeds up, and as they are inserted, the reaction slows down. Even under “meltdown” conditions, where control rods fail, the critical mass of fissile material would be formed slowly. The resulting explosion would be a bad thing, but would not compare with the energy released from a well-designed fission weapon.