# Fission and fusion

Content

Fission:

Nuclear fission can be described as either a nuclear reaction or a radioactive decay process. What defines this process is the splitting of the atom’s nucleus into smaller, lighter nuclei. In the case of the fission of heavy elements, this process typically emits individual neutrons and gamma rays, and releases a very large amount of energy. It is the difference in mass between the original fuel nucleus and the resulting lighter nuclei that results in either the release or absorption of energy. Specifically, for fission to produce net energy, the resulting elements must have less mass than that of the original element. This difference in mass arises due to the difference in atomic "binding energy" between the atomic nuclei before and after the reaction (an example for this is given in the resource ‘Nuclear Energy Calculations’). The energy contained in a nuclear fuel (e.g. 235U, 239Pu) is millions of times the amount of energy contained in a similar mass of chemical fuel. This makes nuclear fission an incredibly dense source of energy. It is nuclear fission which produces the energy of nuclear power plants and also drives the explosive force of nuclear weapons.

After a fission event, the resulting nuclei are no longer the same element as the original atom. Fission is, therefore, a type of nuclear transmutation. This process usually results in two nuclei of comparable sizes, but in around 0.2% of fission events three fragments are created. This special case is known as ternary fission. The fact that the products of fission reactions are not the same every time is a key difference between this and other types of radioactive decay, such as alpha and beta decay which give the same result in every decay reaction. These fission products are generally more radioactive than the original fuel elements and remain dangerously radioactive for long periods of time. This creates a significant issue for the safe disposal and storage of this nuclear waste. An additional issue is the diversion of nuclear fuel for use in weapons. These are the biggest roadblocks to more widespread use of nuclear energy.

The neutrons that are emitted during a fission event are emitted at a very high velocity, typically 7% the speed of light. A material is described as *fissionable* if it undergoes a fission reaction after absorbing one of these fast neutrons. It is preferable for reactor safety and efficiency that the fuel does not depend on these fast, neutron-induced fission reactions. It is preferable that the fuel is able to absorb much slower “thermal” neutrons to undergo a fission reaction. Such fuels are known as *fissile* materials. Some of the most commonly used fissile fuels are 233U, 235U and 239Pu. An example of a fissionable element that is not fissile is 238U, which is the most abundant form of uranium. It will undergo induced fission when impacted by a fast neutron. However, the average energy of the neutrons produced through the fission of 238U is too low to induce further fission. For this reason, a chain reaction is not possible with 238U.

A chain reaction of fission events can take place so long as the neutrons emitted from a fission event create at least one more fission event. Another way of thinking about this is also as the rate of generation of neutrons within the fuel versus the loss of neutrons from the fuel. As long as the rate of generation is greater a chain reaction will take place. A reactor which allows for a sustained nuclear chain reaction is commonly referred to as a critical assembly. In the case of a bomb, where the device is mainly just nuclear fuel, it is called a critical mass. An example of a sustained fission reaction is shown in Figure 1. Critical fission reactors are the most common type of nuclear reactor.

The fundamental physics of the fission chain reaction in a nuclear reactor is similar to a nuclear weapon. However, the two types of devices are very different in design. A nuclear weapon must release all its energy at once, while a reactor is designed to generate a steady supply of useful power. Put simply the main differences are the degree of criticality and the use of fast versus slow neutrons. In a reactor the ratio of neutrons produced in the fuel to those lost is only slightly greater than 1. Also, the time between the production of a neutron to its use in a fission event is on the order of tens of seconds. This results in a rate of power change of about 10% per second. This rate of change is slow enough that it can be controlled by reactor mechanisms. In a weapon, the time between the production of a neutron and its use in a fission event is much quicker, typically on the order of milliseconds. This results in a rate of power change of around 1,000,000% per second. This satisfies the purpose of the weapon, which is to create as much energy as fast as possible. Such a reaction would obviously not be able to be controlled in a reactor. Due to these and other design factors, it not possible for a nuclear reactor to explode with the same destructive power as a nuclear weapon.



Figure 1: Diagram of a fission chain reaction

Fusion:

**Nuclear fusion** is a reaction in which two or more atomic nuclei are combined to form a number of different atomic nuclei and subatomic particles. As with fission, it is the difference in mass between the reactants and products which determines the amount of energy that is either released or absorbed. A fusion reaction that produces a nucleus **lighter** than iron will result in a net release of energy. The opposite is true for [nuclear fission](https://en.wikipedia.org/wiki/Nuclear_fission), where elements **heavier** than iron produce a net release of energy.

Hydrogen to helium fusion is the primary source of energy in all stars. Mid-size stars will also fuse helium into heavier elements such as oxygen, carbon, and nitrogen. Supermassive stars will even fuse elements all the way up to iron. Fusion to heavier elements does not occur in significant amounts as these processes take energy from the star, and when the fusion energy begins to wane the gravitational force collapses the star and if the star is massive enough a supernova results. The supernova is so energetic that elements heavier than iron are created in significant amounts and this is the main way that these heavier elements are created in the universe.

Nuclear fusion has the potential to provide us within an abundant source of energy without the long-lived nuclear waste issues that arise with nuclear fission. This is because the products of fusion reactions we might use for power generation are either stable or have comparatively short half-lives.

Unlike nuclear fission, where we were able to create controlled nuclear fission in a relatively short period of time following our initial discovery of the phenomenon, we have been unable to create controlled nuclear fusion with a net output of energy despite many decades of research. The main reason we have been unable to create controlled nuclear fusion is that it requires temperatures of millions of degrees Celsius. When materials reach these temperatures (or even at much lower temperatures) the electrons separate from the positive nucleus to form free electrons and ions. A material such as this is generally considered the fourth state of matter and is called plasma. Since these ions and electrons are charged particles, combinations of electric and magnetic fields are used to control this material. This is challenging due to the extremely high energy of the plasma particles. A high degree of confinement of this plasma is necessary as any contact with materials at normal temperatures will rapidly cool the plasma and stop any fusion from occurring. There are many different approaches to confining these fusion plasmas, and the most successful to date is a device known as the Tokomak. This is a doughnut-shaped device which confines a plasma in a toroidal magnetic field.