Nuclear Fission and Fusion Reaction

N**uclear fission** is the splitting of a heavy nucleus into two lighter ones. Fission was discovered in 1938 by the German scientists Otto Hahn, Lise Meitner, and Fritz Strassmann, who bombarded a sample of uranium with neutrons in an attempt to produce new elements with Z > 92. They observed that lighter elements such as barium (Z = 56) were formed during the reaction, and they realized that such products had to originate from the neutron-induced fission of uranium-235:

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

This hypothesis was confirmed by detecting the krypton-92 fission product. The nucleus usually divides asymmetrically rather than into two equal parts, and the fission of a given nuclide does not give the same products every time.

In a typical nuclear fission reaction, more than one neutron is released by each dividing nucleus. When these neutrons collide with and induce fission in other neighboring nuclei, **a self-sustaining series of nuclear fission reactions known as** a **nuclear chain reaction** can result (Figure 21.6.2). For example, the fission of ^{235}U releases two to three neutrons per fission event. If absorbed by other ^{235}U nuclei, those neutrons induce additional fission events, and the rate of the fission reaction increases geometrically. Each series of events is called a generation. *Experimentally, it is found that some minimum mass of a fissile isotope is required to sustain a nuclear chain reaction; if the mass is too low, too many neutrons are able to escape without being captured and inducing a fission reaction. The minimum mass capable of supporting sustained fission is called the* ***critical mass****.* This amount depends on the purity of the material and the shape of the mass, which corresponds to the amount of surface area available from which neutrons can escape, and on the identity of the isotope. If the mass of the fissile isotope is greater than the critical mass, then under the right conditions, the resulting supercritical mass can release energy explosively. *The enormous energy released from nuclear chain reactions is responsible* *for the massive destruction caused by the detonation of nuclear weapons such as fission bombs, but it also forms the basis of the nuclear power industry.*

Nuclear fusion, in which two light nuclei combine to produce a heavier, more stable nucleus, is the opposite of nuclear fission. As in the nuclear transmutation reactions , the positive charge on both nuclei results in a large electrostatic energy barrier to fusion. This barrier can be overcome if one or both particles have sufficient kinetic energy to overcome the electrostatic repulsions, allowing the two nuclei to approach close enough for a fusion reaction to occur. The principle is similar to adding heat to increase the rate of a chemical reaction. As shown in the plot of nuclear binding energy per nucleon versus atomic number curve, *fusion reactions are most exothermic for the lightest element*. *For example, in a typical fusion reaction, two deuterium atoms combine to produce helium-3, a process known as deuterium–deuterium fusion (D–D fusion):*

$$2\ {}^{2}_{1}H \rightarrow {}^{3}_{2}He + {}^{1}_{0}n$$

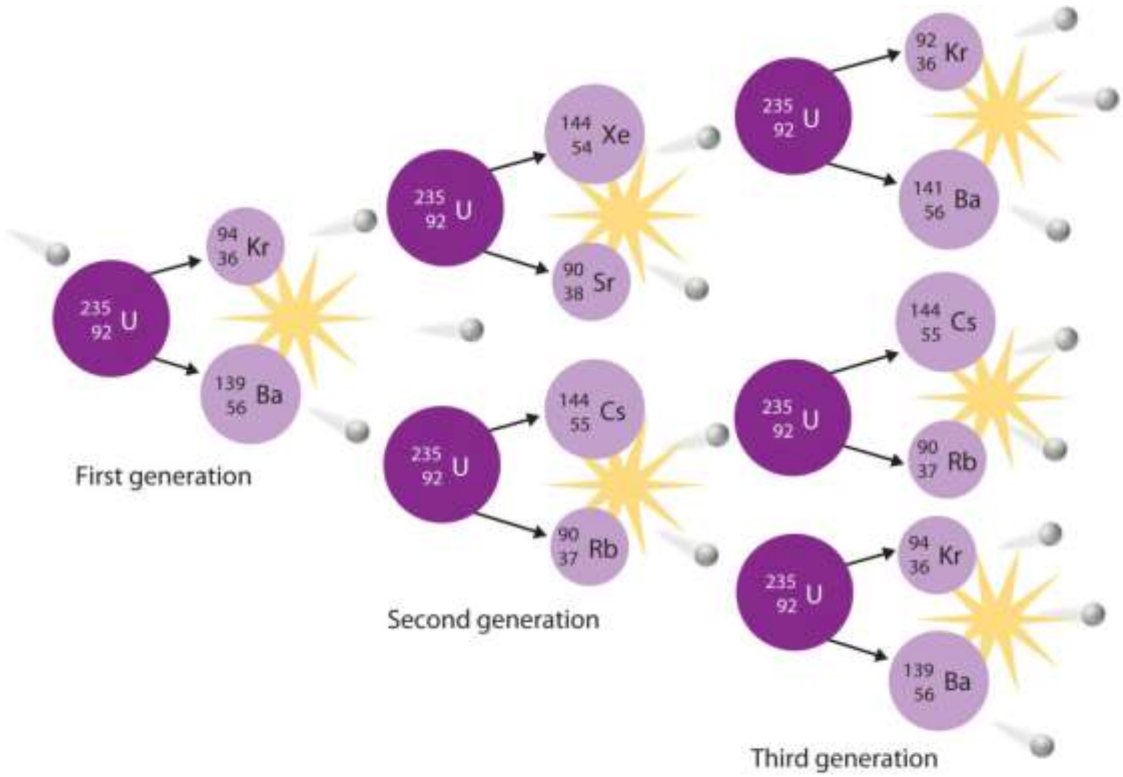


Figure 11***: Because each neutron released can cause the fission of another ^{235}U nucleus, the rate of a fission reaction accelerates geometrically. Each series of events is a generation.***

In another reaction, a deuterium atom and a tritium atom fuse to produce helium-4 (Figure 11), a process known as deuterium–tritium fusion (D–T fusion):

$$^{2}_{1}H+^{3}_{1}H\rightarrow^{4}_{2}He+^{1}_{0}n$$

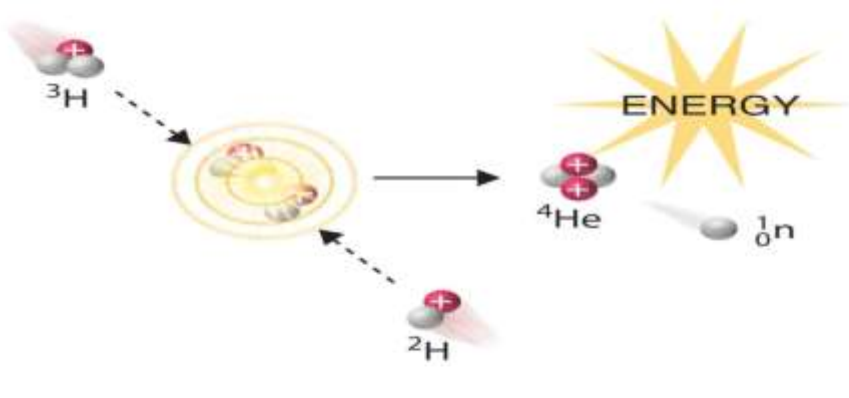


Figure 22: Nuclear Fusion.

In a nuclear fusion reaction, lighter nuclei combine to produce a heavier nucleus. As shown, fusion of ^{3}H and ^{2}H to give ^{4}He and a neutron releases an enormous amount of energy. In principle, ***nuclear fusion can produce much more energy than fission***, but very high kinetic energy is required to overcome electrostatic repulsions between the positively charged nuclei and initiate the fusion reaction.

Initiating these reactions, however, requires a temperature comparable to that in the interior of the sun (approximately 1.5×10^{7} K). Currently, the only method available on Earth to achieve such a temperature is the detonation of a fission bomb. For example, the so-called hydrogen bomb (or H bomb) is actually a deuterium–tritium bomb (a D–T bomb), which uses a nuclear fission reaction to create the very high temperatures needed to initiate fusion of solid lithium deuteride (^{6}LiD), which releases neutrons that then react with ^{6}Li, producing tritium. The deuterium-tritium reaction releases energy explosively. ***In fact, fusion reactions are the power sources for all stars, including our sun.***

Critical Mass

The explosion of a bomb only occurs if the chain reaction exceeds its critical mass. The critical mass is the point at which a chain reaction becomes self-sustaining. If the neutrons are lost at a faster rate than they are formed by fission, the reaction will not be self-sustaining. The spontaneous nuclear fission rate is the probability per second that a given atom will fission spontaneously--that is, without any external intervention. In nuclear power plants, nuclear fission is controlled by a medium such as water in the nuclear reactor. The water acts as a heat transfer medium to cool down the reactor and to slow down neutron particles. This way, the neutron emission and usage is a controlled. If nuclear reaction is not controlled because of lack of cooling water for example, then a meltdown will occur.

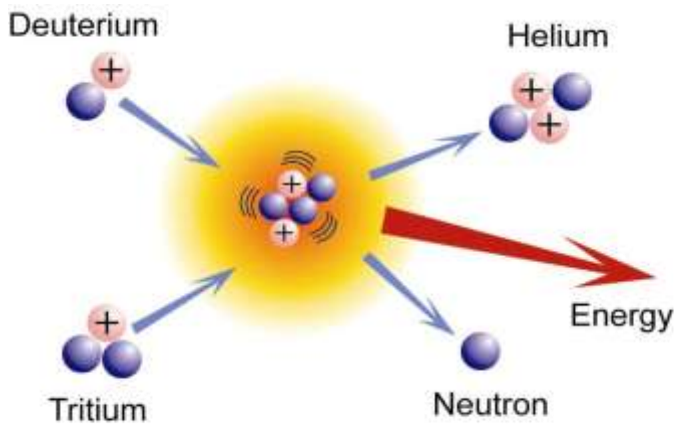
Fusion

Nuclear fusion is the joining of two nuclei to form a heavier nuclei. The reaction is followed either by a release or absorption of energy. Fusion of nuclei with lower mass than iron releases energy while fusion of nuclei heavier than iron generally absorbs energy. This phenomenon is known as **iron peak**. The opposite occurs with nuclear fission.

The power of the energy in a fusion reaction is what drives the energy that is released from the sun and a lot of stars in the universe. Nuclear fusion is also applied in nuclear weapons, specifically, a hydrogen bomb. Nuclear fusion is the energy supplying process that occurs at extremely high temperatures like in stars such as the sun, where smaller nuclei are joined to make a larger nucleus, a process that gives off great amounts of heat and radiation. When uncontrolled, this process can provide almost unlimited sources of energy and an uncontrolled chain provides the basis for a hydrogen bond, since most commonly hydrogen is fused. Also, the combination of deuterium atoms to form helium atoms fuel this thermonuclear process.

For example:

$$\mathbf{H_1^2+H_1^3 \rightarrow He_2^4+n_0^1+energy}$$



However, a controlled fusion reaction has yet to be fully demonstrated due to many problems that present themselves including the difficulty of forcing deuterium and tritium nuclei within a close proximity, achieving high enough thermal energies, and completely ionizing gases into plasma. A necessary part in nuclear fusion is **plasma**, which is a mixture of atomic nuclei and electrons that are required to initiate a self-sustaining reaction which requires a temperature of more than 40,000,000 K. Why does it take so much heat to achieve nuclear fusion even for light elements such as hydrogen? The reason is because the nucleus contain protons, and in order to overcome electrostatic repulsion by the protons of both the hydrogen atoms, both of the hydrogen nucleus needs to accelerate at a super high speed and get close enough in order for the nuclear force to start fusion. The result of nuclear fusion releases more energy than it takes to start the fusion so ΔG of the system is negative which means that the reaction is exothermic. And because it is exothermic, the fusion of light elements is self-sustaining given that there is enough energy to start fusion in the first place

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