Nuclear fission & fusion

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NUCLEAR FISSION

Although in most nuclei the binding energy per nucleon is in the vicinity of 8MeV, in heavy nuclei (A > 200) the binding energy per nucleon is some what smaller (see fig. 4,5). The decrease of binding energy is due to the increasing importance of the electrostatic repulsion. Therefore, it is energetically favourable for a heavy nucleusto split into two fragments, forming two lighter nuclei.

NUCLEAR FUSION

In light nuclei (A < 20), the binding energy per nucleon is small (see fig. 4.5). Light nuclei release energy when they are brought together and are made to fuse into a heavier nucleus.

Nuclear fission of $^{235}_{92}U$

$$^{235}_{92}U + n \rightarrow {}^{236}_{92}U \rightarrow {}^{140}_{54}Xe + {}^{94}_{38}Sr + 2\ neutrons$$

$^{235}_{92}U$ undergoes fission when struck by a neutron. The $^{235}_{92}U$ nucleus absorbs the neutron to become $^{236}_{92}U$ and the new nucleus is so unstable that almost at once it explodes into two fragments. The new nuclei that result from fission are called fission fragments.

Usually fission fragments are of unequal size. Because heavy nuclei have a greater neutron/proton ratio than lighter nuclei, the fragments contain excess of neutrons. To reduce this excess, two or three neutrons are emitted by the fragments as soon as they are formed.

$$^{235}_{92}U + n \rightarrow \, ^{236}_{92}U \rightarrow \, ^{140}_{54}Xe + \, ^{94}_{38}Sr + 2 \; neutrons$$

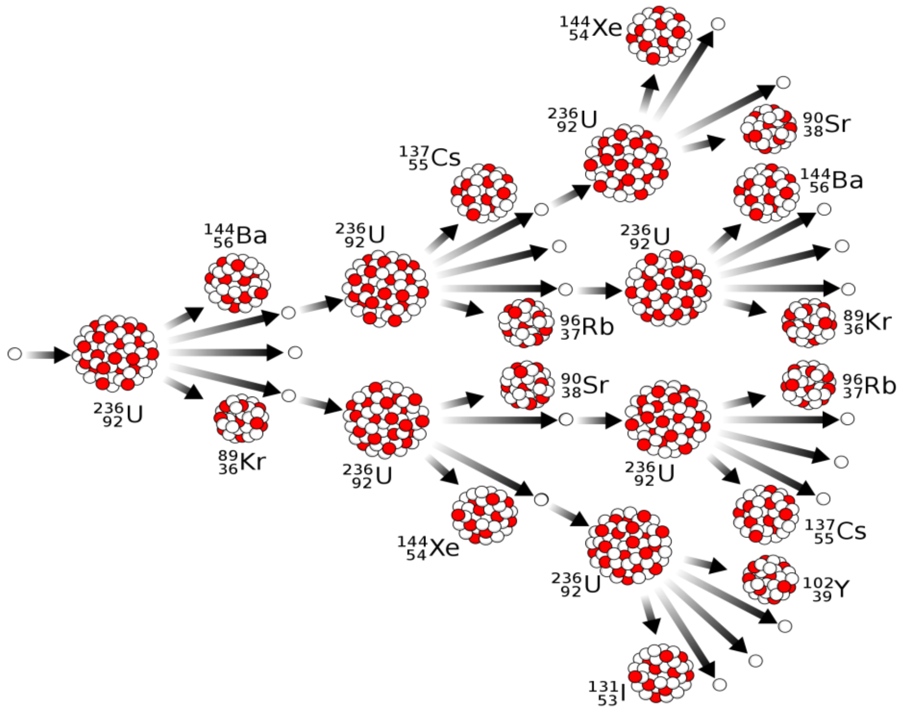
In the case of $^{235}_{92}U$ there is no minimum neutron‘s energy required for fission.

Fission take place even if the energy of the incident neutron is very low, because the binding energy that becomes available when a slow neutron is captured by the nucleus is sufficient to initiate the fission reaction.

In a nuclear fission of a nucleus nearly 200 MeV energy is released. Most of the energy released in fission goes into the kinetic energy of the fission fragments.

The neutrons released during fission leads to fission on other nuclei and a self-sustaining sequence of fission should be possible.

Chain reaction



For such a chain reaction to occur in an assembly of fissionable material, at least one neutron must be produced during each fission to cause another fission. In this case energy will be released at a constant rate which is the case of a nuclear reactor. This situation is called critical.

If too few neutrons cause fissions, the reaction will slow down and stop and this condition is called sub critical.

If the frequency of fission increases, the energy release will be so rapid that an explosion will occur which is the case in an atom bomb and the condition is called super critical.

Self sustained chain reaction is not possible in $^{238}_{92}U$

Naturally occuring uranium contains 99.3 % $^{238}_{92}U$ and the remaining 0.7% is $^{235}_{92}U$.

$^{235}_{92}U$ is a fissile material.

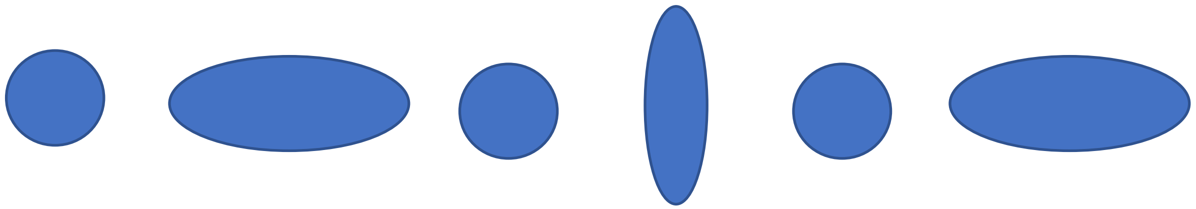
In the case of $^{238}_{92}U$, the minimum neutron energy required for initiating the fission reaction is 1.2MeV. Neutrons of this energy or a larger energy are called fast neutrons. The neutrons released in the fission of $^{238}_{92}U$ are initially fast, but they undergo consecutive inelastic collisions with nuclei before they are finally absorbed in one of these collisions. Thus $^{238}_{92}U$ will not sustain a chain reaction.

Fissile materials

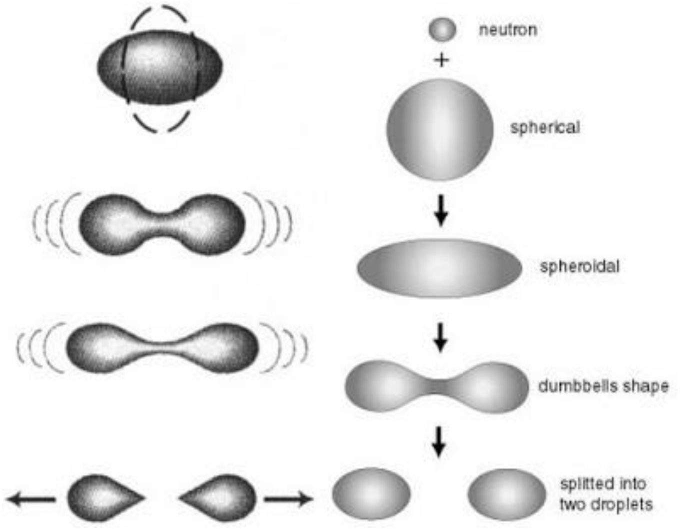
The only other nuclides that can undergo fission with thermal neutrons (slow neutrons) is $^{233}_{92}U$ and plutonium 239. These do not occur in nature but can be produced by the interaction of neutrons with thorium 232 and uranium 238 respectively. These materials can be used as the raw material for the production of fissile isotopes and are called fertile materials. The nuclear reactions which convert these fertile materials into fissile materials are called breeder reactions.

Liquid drop model

Nuclear Fission can be understood on the basis of the liquid-drop model of the nucleus . When a liquid drop is suitably excited, it may oscillate in a variety of ways. The drop in turn becomes a prolate spheroid, a sphere, an oblate spheroid, a sphere, a prolate spheroid again, and so on. The restoring force of its surface tension always returns the drop to spherical shape, but the inertia of the moving liquid molecules causes the drop to overshoot sphericity and go to the opposite extreme of distortion.



Nuclei exhibit surface tension, and so can vibrate like a liquid drop when in an excited state. They also are subject to disruptive forces due to the mutual repulsion of their protons. When a nucleus is distorted from a spherical shape. the short-range restoring force of surface tension must cope with the long-range repulsive force as well as with the inertia of the nuclear matter. If the degree of distortion is small, the surface tension can do this, and the nucleus vibrates back and forth until it eventually loses its excitation energy by gamma decay. If the degree of distortion is too great, however, the surface tension is unable to bring back together and the widely separated groups of protons of nucleus Split into two parts.



Nuclear fusion

- If two nuclei are to fuse, they must be smashed together at high speed. Otherwise their coulomb repulsion would push them apart before the strong attraction has a chance to act. To achieve fusion reactions on a large scale, we need a gas at extremely high temperature (a plasma) in which high speed collisions occur. Such fusion reactions in plasma are called thermonuclear reactions. The temperature need to trigger fusion must be comparable to the temperature at the centre of the Sun. Thus, thermonuclear reactions are most likely for nuclei of very low Z, such as hydrogen in a plasma at extremely high temperature.

Proton-Proton cycle

The basic energy producing process in the Sun is the fusion of hydrogen nuclei into helium nuclei. This can take place in several different reaction sequences. The most common of which is the proton-proton cycle. The total evolved energy is 24.7 MeV per ${}^{4}_{2}He$ nucleus formed. The proton-proton cycle proceeds through a sequence of three steps.

$${}^{1}_{1}H + {}^{1}_{1}H \rightarrow {}^{2}_{1}H + e^{+} + \nu$$

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

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

- The first step is the fusion of two protons, resulting In the formation of deuterium and the simultaneous ejection of an antielectron (positron) and a neutrino. The positron immediately collides with one of the many electrons in the plasma emitting gamma rays.
- The next step is fusion of hydrogen and deuterium, with the formation of ${}_{2}^{3}He$.
- The third step is the fusion of two ${}_{2}^{3}He$ nuclei, with the formation of ${}_{2}^{4}He$(ordinary helium).
- Since the final step requires two ${}_{2}^{3}He$ nuclei, each of the previous steps must occur twice before the final step can occur once.
- Thus, proton-proton chain consumes four protons to make one ${}_{2}^{4}He$ nucleus. The energy released per proton consumed is about 6.6MeV.
- This means that fusion releases more energy than fission per unit mass of fuel consumed.
- The first step of the proton-proton chain releases a neutrino. Thus the centre of the Sun is not only a source of heat, but also a large source of neutrinos. Since the interaction of neutrinos with matter is very weak, the matter in the Sun and in the Earth is nearly transparent to neutrinos. At the Earth, the flux of these neutrinos is about 10^{15} per square meter per second