

Lesson 45: Fission & Fusion

Start talking to someone about nuclear energy, and they'll probably think of two things: nuclear bombs, and the towers of a nuclear power plant like on the Simpsons. Most people view nuclear energy as something to be afraid of, but like most things, once you understand it a lot of the fear disappears.

There are two main types of nuclear reactions that can release energy:

Fission: The process of causing a large nucleus ($A > 120$) to split into multiple smaller nuclei, releasing energy in the process.

- It can start when the large nuclei absorbs a neutron, causing it to become unstable to the point that it falls apart.
- This is the reaction that we use in nuclear power plants and early nuclear weapons.
- Fission is relatively easy to do, but also leaves us with lots of nuclear waste that must be stored for thousands of years before it is safe.

Fusion: The process of causing small nuclei to stick together into a larger nucleus, in the process releasing energy.

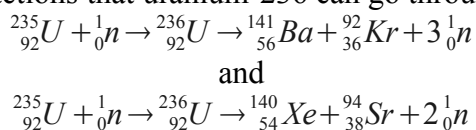
- This is the process that drives our sun, and all other suns.
- We can do it under the right conditions in a lab, but we end up putting in more energy than we get out.
- The left over products of fusion are relatively safe, which is why a lot of research is going into developing fusion reactors.

Fission

The most typical fuel used in a fission reactor is uranium-235.

- In 1939 four German scientists discovered that uranium-235 would become very unstable if it gained an extra neutron, forming uranium-236.
- Uranium-236 is so unstable that a fraction of a second later it will split to form two smaller atoms, and in the process release energy.

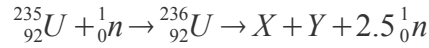
Here are two common fission reactions that uranium-236 can go through...



Some things to notice...

1. Both reactions start the same when we add a single neutron to uranium-235, which forms uranium-236 for a split second.
2. Barium-141, krypton-92, xenon-140, and strontium-94 are smaller nuclei that uranium-236 could split into.
3. At any point in the reaction the conservation of nucleons stays the same.
4. In the first reaction three neutrons were ejected, while in the second reaction only two were ejected. Although it is possible for as many as 5 neutrons to be ejected in some fission reactions, on average it is about 2.5 neutrons.
5. These reactions are exothermic (they release energy).

The basic reaction is written out as...



- X and Y represent any of the smaller nuclei that uranium-236 will split into.

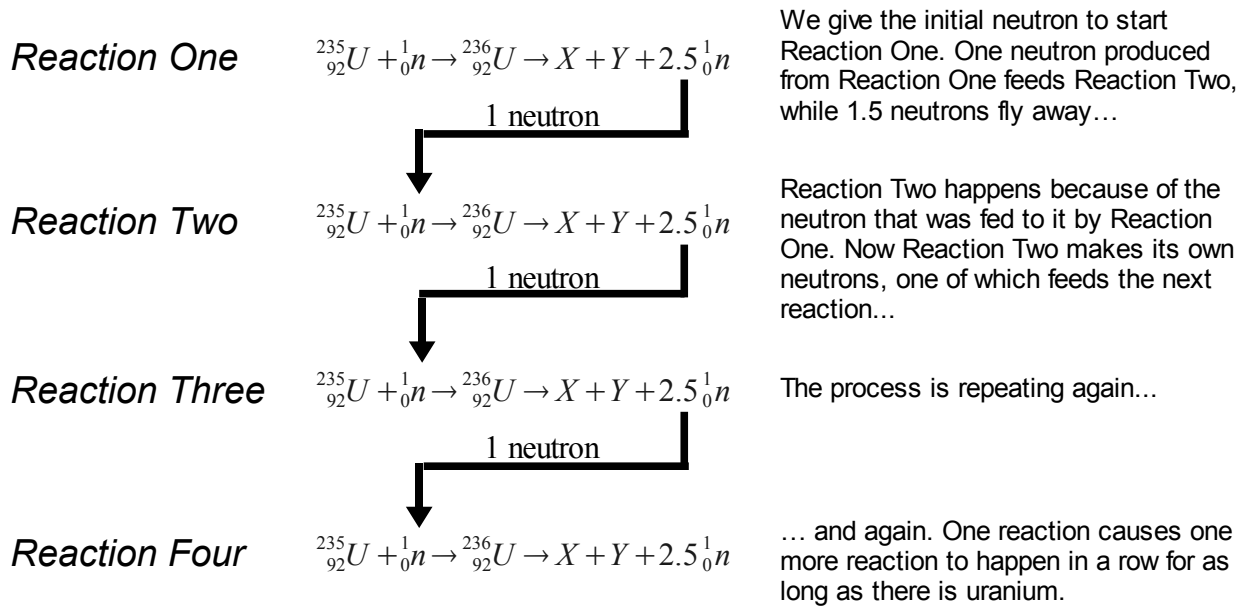
To keep this reaction going, do we need to keep on adding neutrons?

- Well, we could, but it takes energy to isolate neutrons and then throw them at the uranium-235, so this isn't the best idea.
- We do have an average of 2.5 neutrons thrown off each reaction that is successful, so why not just use those?

That's exactly what we do!

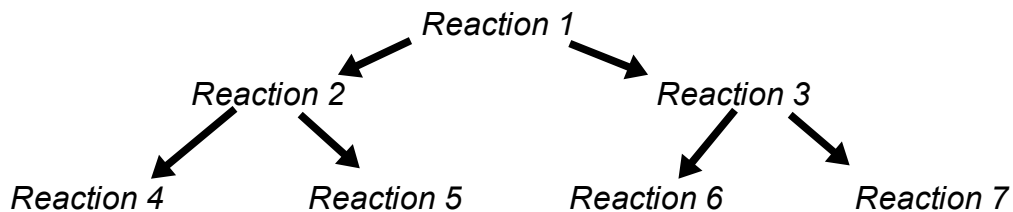
- If exactly one neutron gives rise to another reaction, the self sustaining reaction that results is called **critical**. Each reaction leads to one reaction afterwards. This is a "chain reaction".

Critical Nuclear Reaction



If two or more neutrons give rise to more reactions, the increasing rate of reactions is called **supercritical**. Each reaction leads to multiple reactions afterwards.

Supercritical Nuclear Reaction



- Each reaction leads to multiple reactions, meaning that with each "generation" of reactions the

- number of reactions is increasing exponentially.
- There are a few situations when we want this to happen...
 - in a nuclear bomb, since we want one reaction we kick off to result in a cascade of more and more reactions within a split second
 - when a nuclear power plant is first being started up, until it reaches the number of reactions that we can keep going at the same time. Then it will be stepped down to just a **critical** reaction.
 -
- There is also a situation when we do not want a supercritical reaction, which is when a nuclear power plant is going into a meltdown.
 - This is what started to happen at the [Chernobyl](#) Nuclear Reactor in Ukraine.

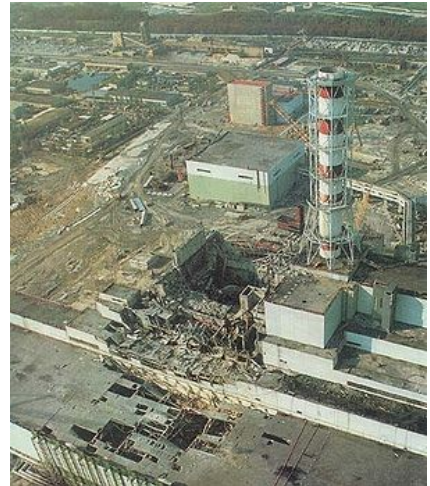


Illustration 1: Chernobyl Reactor Number Four.

If less than one neutron gives rise to more reactions, the decreasing rate of reactions is called **subcritical**.

- For example, let's say you have four reactions, but the neutrons from only three of them feed later reactions, and of those three only two continue, then down to one... the reaction will eventually die out.
- This is what happens when you shut down a reactor.

Reactors use control rods to control the rate of the reaction.

- Made from elements such as boron and cadmium, control rods are very good at absorbing neutrons.
 - If a reaction is going **supercritical**, drop the control rods further into the core to absorb extra neutrons and the reaction slows.
 - If the reaction is going **subcritical**, pull the control rods out further, which lets more neutrons react and get more reactions going again.

Nuclear Reactors

All reactors that we currently use go through the process outlined above. There were a couple of problems back in the 1940's that needed to be figured out before reactors could work.

Problem One

The 2.5 neutrons released in the fission process are moving really fast, in fact too fast to be able to be absorbed by the next uranium-235 in the chain.

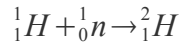
- We need to be able to slow them down. Something that slows down neutrons in a reactor is called a **moderator**.
- If you want something to slow you should hit it against something about the same size, so it would be best if we could get these fast moving neutrons to hit some different neutrons.
 - Unfortunately, naturally occurring neutrons are very unstable, so we'd be better off with something about the same size as neutrons. Hmmm, maybe **protons**!
 - A cheap source of a bunch of protons is water! All those hydrogen atoms in water are made up of a single proton orbited by an electron.

So, our solution to the first problem is to use water as a moderator to slow down the fast moving neutrons from one reaction, allowing them to interact with the next uranium nucleus in the chain.

Problem Two

Water is mostly made up of hydrogen-1 atoms.

- Hydrogen-1 doesn't just slow down neutrons, they usually **absorb** neutrons. This prevents them from going on to the next part of the reaction.



- This means that the water has absorbed the neutron that hit it, forming hydrogen-2, also called **deuterium**.
 - Since the water molecules now have two extra neutrons (one on each hydrogen), the water is atomically more heavy, so we often call it **heavy water**.

There are three solutions to this problem:

1. *Use enriched uranium in the reactor.*

This just means that the uranium ore is more carefully refined to contain more U-235, so the critical reactions have a better chance of happening even if some neutrons are absorbed.

2. *Use heavy water in the reactor.*

Rather than starting with regular water, intentionally put heavy water in as your moderator. Hydrogen-2 in the heavy water will not absorb many more neutrons. This way you can use regular uranium ore.

3. *Use graphite (carbon) rods.*

It turns out this works really well as a moderator. It is a popular method for building reactors in the former Soviet Union and Britain. There is one big problem... if things get too hot in the reactor, carbon can actually burst into flames (they're basically giant BBQ briquettes). This is what happened at Chernobyl.

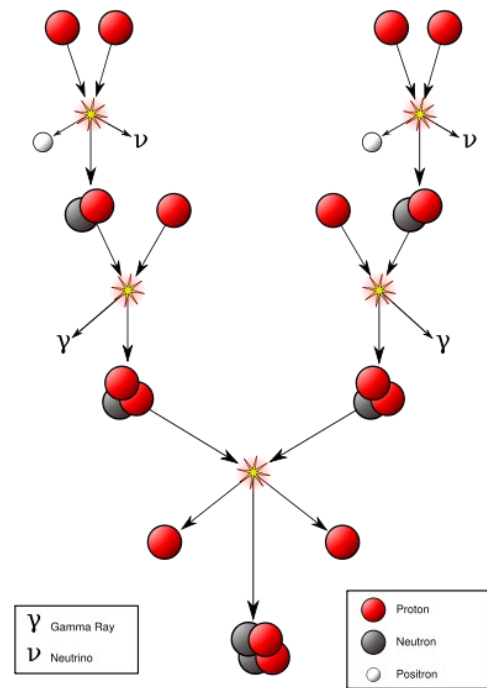
Fusion

By the time the 1920's rolled around, physicists had figured out that the Sun was made from about 73% hydrogen and 27% helium.

- The suggestion was made that maybe hydrogen nuclei fuse together to form helium nuclei.
 - This would fit, since four hydrogen nuclei (four protons) have just a little more mass than a helium nucleus. It would make sense the mass that was missing after fusion would have been converted to energy ($E=mc^2$).
- This very basic fusion, called a **proton-proton chain**, is the source of energy for stars like our Sun.

So why don't we use fusion instead of fission here on Earth in our nuclear reactors?

- Unfortunately at this stage of technology we haven't worked out all the bugs yet.
- We can build and run fusion reactors right now, but we end up putting in more energy than we get out.
 - This is because the fusion reactions require intense heat and pressure to allow fusion to happen.
 - There is a great deal of research working on **cold fusion**, the ability to cause fusion to happen at lower temperatures.



*Illustration 2: Proton-proton chain.
Image courtesy of [Borb](#).*