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.

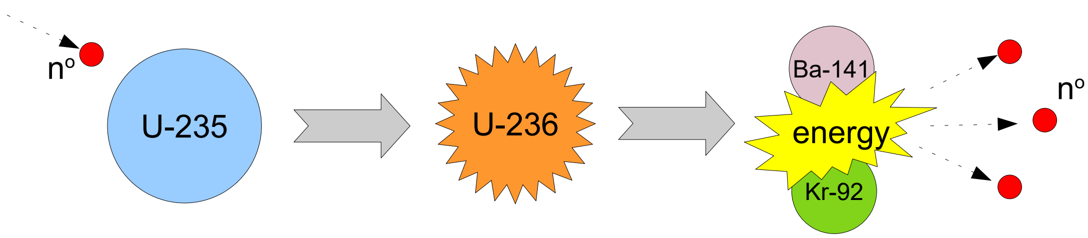
Fusion: The process of causing small nuclei to stick together into a larger nucleus, in the process releasing energy.

- 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 written out...

$${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{236}_{92}U \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3\,{}^{1}_{0}n$$

and

$${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{236}_{92}U \rightarrow {}^{140}_{54}Xe + {}^{94}_{38}Sr + 2\,{}^{1}_{0}n$$

The basic reaction is written out as…

$${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{236}_{92}U \rightarrow X + Y + 2.5\,{}^{1}_{0}n$$

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

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 laws of nucleons and charge are obeyed.
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 as shown in the basic reaction. You can't really have half a neutron, but we're just looking at the average mathematically.
5. These reactions are exothermic (they release energy).

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

Reaction One $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{236}_{92}U \rightarrow X + Y + 2.5\,^{1}_{0}n$

We give the initial neutron to start Reaction One. One neutron produced from Reaction One feeds Reaction Two, while 1.5 neutrons fly away…

1 neutron

Reaction Two $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{236}_{92}U \rightarrow X + Y + 2.5\,^{1}_{0}n$

Reaction Two happens because of the neutron that was fed to it by Reaction One. Now Reaction Two makes its own neutrons, one of which feeds the next reaction...

1 neutron

Reaction Three $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{236}_{92}U \rightarrow X + Y + 2.5\,^{1}_{0}n$

The process is repeating again...

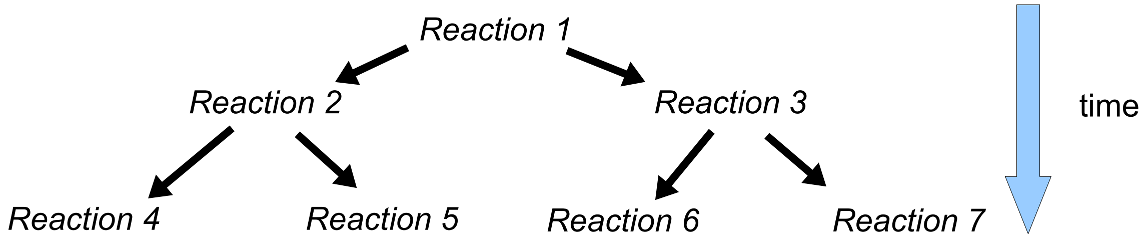
1 neutron

Reaction Four $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{236}_{92}U \rightarrow X + Y + 2.5\,^{1}_{0}n$

… and again. One reaction causes one more reaction to happen in a row for as long as there is uranium.

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 or 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 exponentially 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.

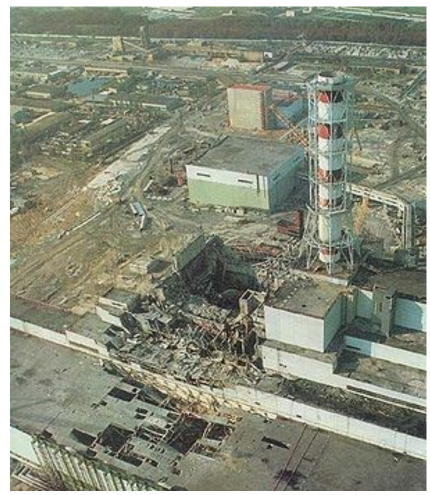
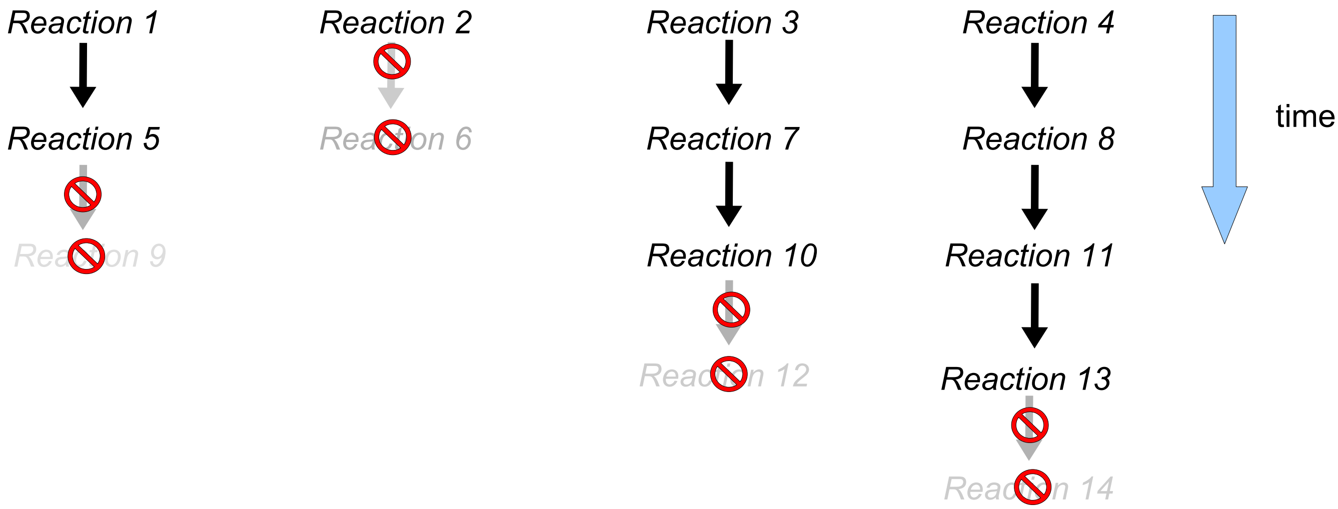


Illustration 1: Chernobyl Reactor Number Four.

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

- For example, lets 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.

Subcritical Nuclear Reaction



Nuclear Reactors

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 to **critical**.
  - If the reaction is going **subcritical**, pull the control rods out, which lets more neutrons react and get more reactions going again to **critical**.

Nuclear reactors had a problem identified in the 1920s-40s that needed to be figured out before reactors could work.

- 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***!

This leads to three possible materials that can be used as moderators...

Moderator 1: Water

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.

- The hydrogen in water are mostly 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.

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

A way to get around this is to use enriched uranium.

- There are still some neutrons that just slow down, so we have to give them a better chance of hitting a U-235 nucleus.
- We refine the uranium so it has higher amounts of U-235 nuclei in them. This increases the probability of those few neutrons hitting the U-235 to keep the fission reaction critical.
- This method is used by reactors in the USA.

Moderator 2: Heavy Water

So, recall that if the hydrogen in a water molecule absorb a neutron, they go from H-1 to H-2. This hydrogen with one proton and one neutron is so special it gets a name... **deuterium**.

- Since the hydrogen in 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**.

Rather than starting with regular water in your reactor, intentionally put heavy water in at the start as the moderator.

- Hydrogen-2 in the heavy water will not absorb many more neutrons. It will just let the neutrons flying around hit it and slow down.
- This way you can use regular uranium ore. CANDU (**CAN**adian **D**euterium **U**ranium) reactors use this method.

Moderator 3: Graphite

Hey, what happened to the water! It turns out graphite (carbon) 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 oxygen gets into the reactor, carbon can actually burst into flames (they're basically giant BBQ briquettes). This is part of what caused the explosion 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.

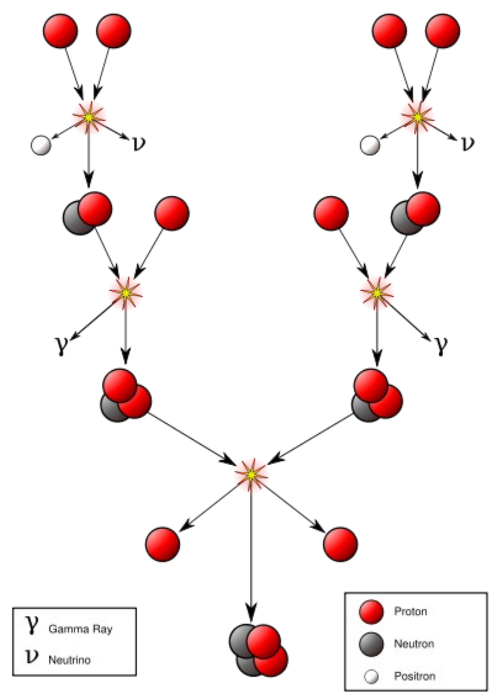


Illustration 2: Proton-proton chain. Image courtesy of Borb.

So why don't we use fusion instead of fission here on Earth in our nuclear reactors? For each kilogram of fuel, fusion actually makes more energy than fission, so it would make sense to build fusion reactors to supply us with energy.

- The problem is obvious if we think of where fusion naturally occurs... inside stars at immense pressure and

temperature (around 14 million Kelvin).
    - It is almost impossible to recreate these exact conditions on Earth in a reactor we build, so current research uses intense magnetic and electric fields, usually along with lasers.
- In 2014 scientists at the Lawrence Livermore National Laboratory produced a controlled fusion reaction with more output than input for the first time, but just barely!
    - They used a fuel source the size of a pin head and only lasted for 150 ps, so it is only at the experimental level.

Unfortunately, we are pretty good at ***un***controlled fusion.

- Thermonuclear weapons first use a fission device to create the initial temperature and pressure needed to drive the fusion process where most of the energy comes from.
- These weapons can be built smaller and with more explosive energy than regular fission bombs.

In 1989 Stanley Pons and Martin Fleischmann at the University of Utah claimed to have performed **cold fusion** that "anyone could do with a mayonnaise jar."

- They skipped publishing their results and instead had a press conference to announce their results.
- It was later proved false when the experiment could not be reproduced.

Homework

p819 #2
p824 #1, 4, 6, 8
p826 #3, 5-8, 10, 12, 14, 16, 25, 30