Chapter 10

Nuclear Chemistry

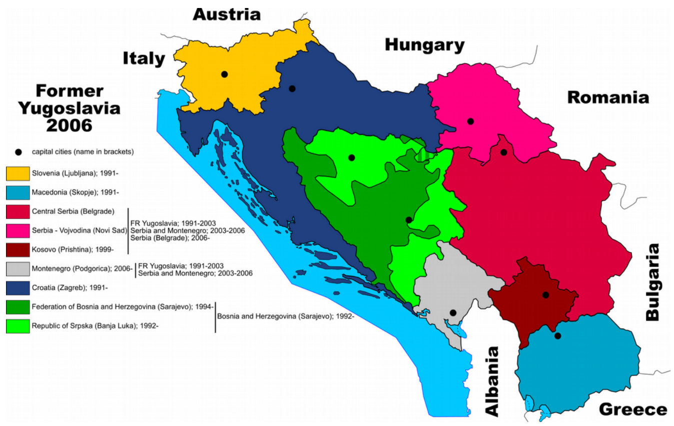
These are some of the internal parts of a B61 thermonuclear weapon. This attractive and functional nuclear device has a "dial-a-yield" feature so that the discerning user can set it to have anywhere from a 0.3 to 340 kiloton explosive yield. It's turn-ons include PBX-9502 insensitive high explosive and lithium-6, while turn-offs include the de-escalation of nuclear tensions throughout the world. It is known to be a Libra.

10.1: Radiation

Some people are stable. Some people are unstable. We expect stable people to hold down jobs and pay their rent on time. We expect unstable people to rob liquor stores and take their pants off in church. Such is life.

Atoms are the same way. Some atoms are stable and they just sit there like big boring lumps of matter. Other atoms are not stable and their nuclei break apart into smaller parts. We refer to these as **radioactive** atoms.

If you think about it for a second, it's really not that surprising that some nuclei might be unstable and want to fly apart. Consider this: The particles you find in a nucleus are neutrally-charged neutrons and positively-charged protons. The neutrons are pretty much cool with whatever, but if you pack enough protons into one place, they simply won't stick to each other anymore. When this happens, the nucleus breaks apart and undergoes **radioactive decay** into smaller bits.



A similar phenomenon happened in post-cold war Yugoslavia, where the republics which had comprised the country went their separate ways. Which is a story for your history teacher.

Not every nucleus is unstable. If they were, we'd have shoes and cats and stuff decaying all over the place, which would be both impractical and gross. Isotopes that undergo nuclear decay are called **radioisotopes**, while stable isotopes are referred to as, well, **stable.**

There are several different types of radiation that occur when an atom decays, including the following:

- **Alpha decay (α)**: Alpha decay occurs when a nucleus gives off an alpha particle (a helium-4 nucleus) in its efforts to become more stable. After the alpha particle is given off, a new, smaller atom is left over:

$$^{111}_{54}Xe \rightarrow ^{107}_{52}Te + ^{4}_{2}He$$

- **Beta decay (β)**: In beta decay, a nucleus gives off a beta particle (an electron) to become more stable. Again, this results in a more stable atom:

$$^{16}_{6}C \rightarrow {}^{16}_{7}N + {}^{0}_{-1}e$$

- **Gamma decay (γ):** In gamma decay, a gamma ray (which is essentially just really high energy light) is given off by the nucleus to decrease its energy:

$$^{60}_{27}Co* \rightarrow {}^{60}_{27}Co + {}^{0}_{0}\gamma$$

  The * next to cobalt shows that the nucleus has extra energy, which is given off when the gamma ray is emitted.

Note: There are other forms of nuclear decay as well, but we'll stick to these for now. Stay tuned for more information in future science classes.

Balancing Nuclear Equations

Just as it's important to balance chemical equations, it's also important to balance nuclear reactions. This is done by making sure the atomic masses and atomic numbers are the same for the elements on each side of the equation. Fortunately, the numbers to the left of each particle in the equation help us to do this. Simply make sure that the numbers add up on both sides of the equation and you're in good shape.

An example: Let's write the equation for the alpha decay of radium-226. Just from the very start, we know that our "reagent" will be radium-226 and one of our products will be a helium-4 nucleus:

$$^{226}_{88}Ra \rightarrow {}^{4}_{2}He + something$$

Looking at this equation we see that the mass of radium is 226 and the mass of helium is 4 – the difference is 222, so that must be the mass of the other particle formed. Likewise, the atomic number of radium is 88 and that of helium is 2, so the other particle must have an atomic number of 86 (the periodic table tells us that this is radon). Completing this equation, we find that:

$$^{226}_{88}Ra \rightarrow {}^{4}_{2}He + {}^{222}_{86}Rn$$

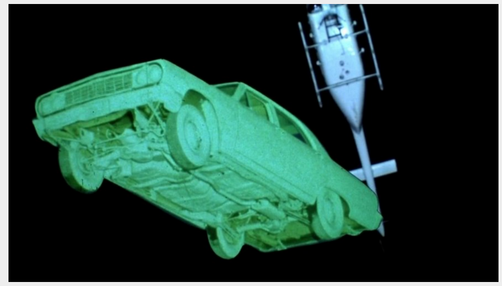
Will Radiation Kill You?

When people hear of radiation, they usually think of some terrible nuclear disaster that has melted the faces off of hundreds of people. Though there haven't been very many nuclear accidents over the years and the ones that have occurred usually aren't all that bad, there are some things that you should probably understand about radiation, lest you start freaking out.

There are two types of radiation. **Ionizing radiation** is radiation that knocks electrons off of atoms that it hits (i.e. it makes them into ions). Ionizing radiation consists of high energy light (gamma rays, x-rays) and the various particles given off during radioactive decay (alpha particles, beta particles, other exotic particles we haven't talked about). **Non-ionizing radiation** is radiation that doesn't knock electrons off of atoms they hit – these consist of electromagnetic waves that are less energetic than visible light (infrared light, microwaves, radio waves). Note that in a broad sense, the term **radiation** just refers to something that is given off by something else. Generally speaking, we worry more about ionizing radiation than non-ionizing radiation when it comes to face melting.

Is All Ionizing Radiation Equally Bad?

Some forms of ionizing radiation are worse than others. Alpha particles are relatively large, so if you're exposed to alpha radiation it can't penetrate your skin far enough to cause any real damage. Beta particles (electrons) are smaller and better able to penetrate the body, but aren't a huge matter of concern unless you absorb a lot of them. Gamma rays, on the other hand, penetrate the body really well and are good at tearing up atoms. This is bad.



On the plus side, radiation is handy if you're interested in building a flying Chevy Malibu.[1]

Interestingly, radioactive materials come in very handy if you want to kill bad things in your body. For example, cancerous tumors can be killed by exposing them to beams of x-rays, gamma rays, or various charged particles – this can be done either externally by shooting beams of radiation at the affected area, or internally by implanting pellets containing the radiation source. Though this treatment *does* have the effect of causing radiation damage to surrounding tissue, this is vastly preferable to leaving the cancer tumor untreated.

Scientists use Geiger counters to detect radioactive particles. Geiger counters consist of a chamber that's placed under high voltage and filled with gas molecules. When radioactive particles enter this chamber, they cause a small amount of electricity to be discharged, and it is this electrical discharge which is measured by the Geiger counter.

This happy man is currently coming up with an explanation for why the squirrels in your neighborhood glow in the dark.

1 *Go see Repo Man (1984) if you want to understand what I'm talking about. Heck, see it anyway.*

10.2: Half-lives

You've probably heard the term "half-life" before, and you probably know it has something to do with nuclear something or other. Interestingly, this belief about half-life happens to be only half-true.

Half-life refers to the amount of time it takes for a process to proceed 50% to completion. If you're flipping coins, the half-life of heads is "one flip" because after one flip 50% of the coins should be heads. For nuclear reactions, the half-life of an isotope is the amount of time it will take for half of the atoms of that isotope to undergo radioactive decay.

To understand how this concept works, let's go back to the idea of flipping a coin that I had a moment ago. Coin flipping is said to be a **statistical process** because we can predict what should happen for a large number of things, but can't predict what any of those particular things will do. For example, if we flip 1000 coins, we can guess that about 500 will be heads and 500 will be tails. However, we don't have any idea *which* of those 500 coins will be heads or tails. We can, however, guess that every time we flip the coins, one half of the coins that were tails should turn to heads.

Try It At Home!

If you try the coin flipping example above, you'll almost certainly find that after one flip, you don't *have either 500 heads or 500 tails. This is another feature of statistical processes: You can usually figure out what* should *happen based on probability, but you can't guess* exactly *what will happen. As a result, you probably won't get 500 heads, but you'll almost certainly get something between 450 and 550.*

If you live somewhere with different coinage, substitute "heads" with "lion" and "tails" with "whatever that other thing is."

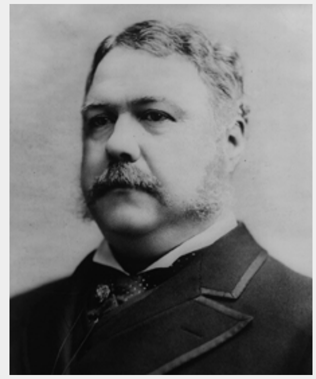
Now, you might be thinking to yourself that this doesn't really mean much. After all, if half of the coins flip to heads in one flip, shouldn't the other half flip over on the second?

Not quite. It's not that 50% of the *original* number will flip every half-life. It's 50% of the *remaining* amount. As a result, if, after one flip, we have 500 coins that remained tails, a second flip should cause half of *those* coins (i.e. 250 coins) to flip over to heads. As a result, after two half-lives, only 750 of the coins will have flipped to heads. Likewise, on the third flip, half of the 250 remaining coins (i.e. 125 coins) will flip to heads, so we can expect 875 heads at that time.

Let's get back to nuclear decay. What this means for us in terms of isotopes is that the amount of an isotope will be halved after a half-life has passed. For example, carbon-14 has a half-life of 5730 years. This means that if a sample of carbon-14 initially weighs 100 grams, there will be 50 grams of carbon-14 after 5730 years, 25 grams after (2 x 5730 =) 11500 years and so forth.

Radiocarbon Dating Fun!

It turns out that very old artifacts are dated using exactly the process described here. Carbon-14 is generated by natural processes in the atmosphere, and while things are alive they take in a constant and predictable amount of carbon-14. However, once living things die, they no longer take in carbon-14, so the ratio of carbon-14 to other forms of carbon decreases over time. By measuring how much of the carbon-14 is missing, the amount of time elapsed since something died can be accurately determined.



Radiocarbon dating can be used to determine the age of dead people such as U.S. President, Chester A. Arthur.

10.3: Nuclear Fission and Fusion

As we mentioned in 10.1, radioactive decay occurs when an unstable nucleus breaks apart to become more stable. This can be done in a bunch of different ways, and I'm not going to go over them again. Section 10.1: Know it, love it.

However, what happens if nuclei *aren't* radioactive? Can we *force* them to undergo nuclear reactions?

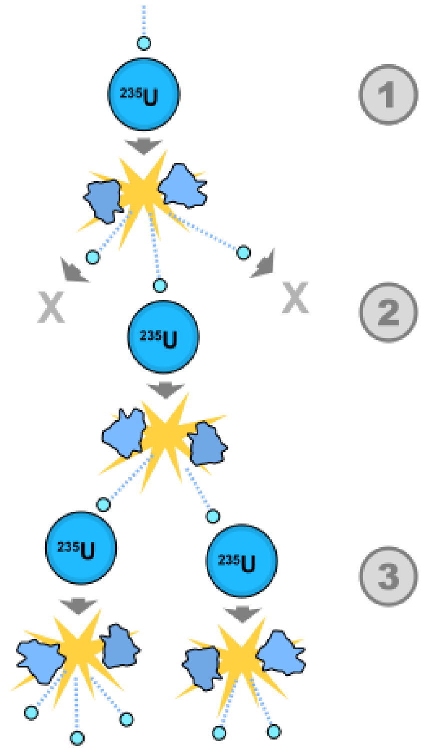
Why yes. Yes we can. And it's *terrifying*!

Terrifying

\Nuclear Fission

Generally speaking, atomic nuclei are pretty happy just hanging around doing nothing. Many nuclides aren't radioactive and will sit in one place doing nothing forever. Other nuclides are radioactive and will sit in one place for varying periods of time, depending on their half-lives. However, what happens if you decide that you want atomic nuclei to change *right now?*

If you want to make nuclei do interesting things, you've got to put a lot of energy into them. In 1938, chemists Otto Hahn and Fritz Strassmann were able to do exactly this. By irradiating uranium-235 with a beam of neutrons, they were able to break the U-235 nuclei into smaller nuclei and additional neutrons. These additional neutrons could then go on to hit other U-235 nuclei, causing the reaction to spread throughout the entire sample in a chain reaction.



1. When a U-235 nucleus is hit with a neutron, it is broken into two smaller nuclei (shown as the squished looking blue blobs) and additional neutrons (more little blue circles). 2. In turn, each of these neutrons are free to hit other uranium nuclei, continuing the process. 3. If this process can be maintained at a high enough rate, lots and lots of heat is generated.

In each step of this process, additional neutrons are given off that can continue the reaction. However, for this to happen there need to be enough target atoms hanging around so that most of the neutrons are able to collide with them to make new neutrons. The minimum mass of this material to make this happened is called a **critical mass**. The entire process by which atoms are broken into smaller ones is called **nuclear fission**.

You're probably already aware that nuclear reactions give off vast amounts of energy. The big question: Where does the energy come from? The answer: $E = mc^2$.

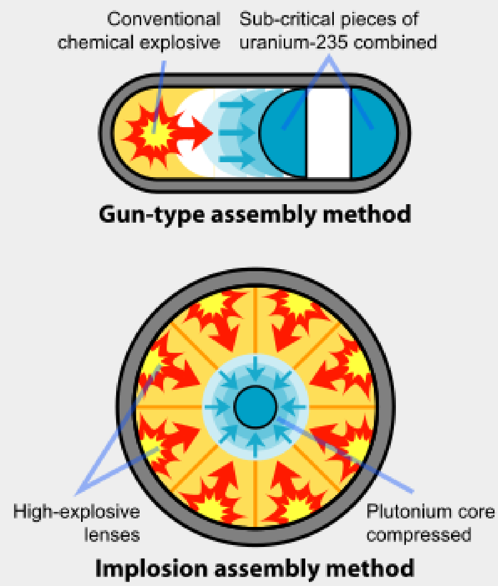
When nuclei break apart via fission, the mass of the stuff that's made is less than that of the mass of the stuff that was initially present. This isn't because the law of conservation of mass is a lie, though – it's because Einstein told us that mass and energy could be inter-converted using his famous equation. The difference in mass between the parent atom and the stuff made when it undergoes fission isn't very big, but when we convert it to energy using Einstein's equation, it is equivalent to a just gigantic amount of energy. It is in this way that a chunk of plutonium weighing only three kilograms (about the weight of a small cat) can generate enough energy to destroy entire cities.

Let's Have A War![2]

If you want to blow up a whole bunch of stuff at once, you'll need to obtain a critical mass of fissionable material such as plutonium-239. This can be done in two ways:

- *Gun-type nuclear weapons fire two large chunks of fissionable material into each other to make a large critical mass.*
- *Implosion devices squish a smaller bit of fissionable material into a very small space to achieve criticality.*

Whichever way you choose, you can be certain that you'll have a critical mass of fissile material available for your strategic defensive or tactical offensive needs.



If you're interested in seeing nuclear fission processes without having your eyes melt, you can do so by visiting a nuclear power plant. In a nuclear plant, a subcritical quantity of fissile material is collected and the neutrons given off by spontaneous fission cause neighboring atoms to undergo fission as well. Though you might think that this would lead to a runaway chain reaction, there is a small enough quantity of fissile material that this simply cannot happen.

2 *For those of you not into punk rock, this is a reference to the song of the same name by Fear. (https://www.youtube.com/watch?v=yJAlIHsXcLY)*

Meltdown!

You may have heard of nuclear power plant meltdowns happening at Three Mile Island (US), Fukushima (Japan), and Chernobyl (USSR, now Ukraine). In a nuclear meltdown, the temperature of the nuclear core (i.e. the fissile material) gets out of control and it melts, forming a great big bunch of melted nuclear sludge. Generally speaking, the containment vessels in which the nuclear reactions occur are designed to contain a large quantity of melted nuclear material long enough that it has time to cool. Unfortunately, if there is an explosion inside of these containment vessels (as was the case in both Fukushima and Chernobyl), the containment vessels can be breached, releasing radioactive gas into the atmosphere. Fortunately, this doesn't happen much, which is why nuclear power is, statistically speaking, extremely safe.[3]

Move along. Nothing to see here.

Nuclear Fusion

Unlike nuclear fission, which occurs when large nuclides break apart to make smaller ones, nuclear fusion occurs when smaller nuclides are crammed together to make bigger ones. Though these may seem like they're pretty much the same process in reverse, there are a few major differences:

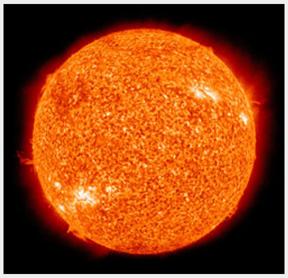
- **The nuclides are of different sizes**. Whereas fission usually involves large nuclides like U-238 breaking into smaller ones like Sn-132 and its buddies, fission generally involves really small nuclides such as hydrogen-2 (aka. deuterium) and hydrogen-3 (aka. tritium) combining to make slightly less tiny nuclides like helium-4:

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

- **The amount of energy released in fusion is much larger**. Roughly 35 times larger. This means that if you want to make a fabulously huge amount of energy, fusion is your friend.[4]

Stars: Our Explody Friends

The reason stars are so unbelievably hot is that nuclear fusion is the process that generates their energy. As stars get older, the products of one fusion process become the starting materials for others.



This picture of the sun is shown smaller than actual size.

3 *Wind and nuclear are both much safer than other forms of power generation.*

4 *Source: http://www.physlink.com/education/askexperts/ae534.cfm.*

- **Fusion reactions are much harder to initiate than fission reactions**. Fission reactions spontaneously occur in fissile materials when neutrons created by spontaneous fission bounce around and cause neighboring atoms to break apart. Fusion reactions, on the other hand, require temperatures of about four million Kelvin to get started. For this reason, it's not very likely that we'll see fusion reactions anytime soon.[5]

The Main Ideas in Chapter 10:

- Radiation occurs when nuclei give off various particles to become more stable. These include alpha particles (helium-4 nuclei), beta particles (electrons), and gamma rays (high energy light). There are others, but we won't worry about them now.
- The half-life of a process measures how long it takes for half of the starting material to become product. In the case of nuclear processes, it's a measure of how long it takes for half of the initial atoms of the unstable isotope to undergo nuclear decay.
- The concept of half-life is a statistical one. While it can predict the behavior of large numbers of particles, it can't predict the behavior of any particular particle among them.
- Radiocarbon dating uses the quantity of carbon-14 in a formerly living thing to determine its age, using the 5,730 year half-life of carbon-14.
- Nuclear fission occurs when an unstable nucleus breaks into smaller ones, giving off neutrons which can, in turn, break apart others.
- A fission process reaches critical mass when the number of neutrons given off is large enough for the process to be self-sustaining.
- Fusion processes occur when smaller nuclides combine to make larger ones. They're hard to control, but generate absolutely insane amounts of energy.

What $4.2 Billion Can Buy

If you've got $4,200,000,000 lying around, you can purchase yourself a laser-powered nuclear fusion device. Well, sort of, Like the National Ignition Facility at the Lawrence Livermore Labs in California, it probably won't actually cause fusion to occur. And if it does, it won't actually be useful for producing nuclear power. But it's very cool to look at.

These men are looking at something at the NIF facility. You can tell it's interesting because one of the men at the right is pointing at it.

5 *This doesn't mean, however, that we can't get fusion reactions to take place. Hydrogen bombs are uncontrolled fusion reactions that are triggered by regular old fission bombs. For this reason, hydrogen bombs thermonuclear weapons are sometimes referred to as "multistage weapons." (http://www.johnstonsarchive.net/nuclear/diagthermon.html).*

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