Nuclear Chemistry Part 2: Fusion and Fission - Crash Course Chemistry #39

Crash Course: Chemistry
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===== Introduction =====

As I said before chemistry is, like many aspects of your own life, all about a search for stability. Last week we talked about radioactive decay and how atomic nuclei get rid of various particles in order to become more stable. But what is this illusive stability that all things seem to be striving for exactly?

In nuclear chemistry it simply has to do with keeping the nucleus together. If the nucleus is going to break apart, then that's not going to be something that lasts very long. Stability really, is kind of just a way of saying, it can exist. And the amount of energy, that holds each proton or neutron in an atom's nucleus, is the same amount that's released when it's removed. This is known as binding energy and it's one of the fundamental principles of nuclear chemistry. It's actually what we mean when we talk about nuclear energy.

Now I'm not going to lie to you, nuclear chemistry is terribly complicated, but we have a way of understanding it that, while not exactly simple, is one I'm sure you've heard of. The binding energy of an atom is calculated with the formula $E = mc^2$. Probably the most famous equation in the world and since it was first hit upon by a young patent clerk in 1905 it has become synonymous with scientific genius. Part of why it's so famous, I like to think, is because the logic behind it is so elegantly simple and yet totally counter intuitive, but it's probably also famous because it's important. It explains one of the most powerful sources of energy known to humanity.

(Crash Course Intro)

===== Law of Conservation of Energy =====

$E = mc^2$ is formally known as the mass-energy equivalence formula and it states that mass is interchangeable with energy. Okay, there is a lot there, in what I just said.

To tease it apart consider the nucleus of an atom of oxygen, eight protons and eight neutrons. Collectively, by the way, these particles are known as nucleons. If you were to add up all the individual masses of all sixteen nucleons separately and then compare that to the total mass of an actual oxygen nucleus, you'd find that there's a difference between the two. Specifically the mass of the nucleus, exactly 15.99 atomic mass units, is lower than the mass of its individual nucleons put together, in this case 16.13 amu's.

That mass went somewhere. That "missing mass" in the nucleus, known as its mass defect, is actually present in the form of energy. It's the energy that holds the nucleons together so for example the mass defect for an oxygen atom is negative 2.269×10^{-28} kilograms. To find out how much binding energy that missing mass amounts to, you can use it as the 'm' in Einstein's formula.

This ingenious little equation relates mass and energy by a simple proportionality constant, and thanks to Einstein we know that constant is the square of the speed of light, or c^2. Solve for 'E' and you find that the binding energy in that oxygen nucleus is 2.04×10^{-11} joules, with the negative sign indicating that the energy is being released. Now of course 2.04×10^{-11} is a very small number. That might surprise you, but hold the phone, that is just for one single nucleus. If we multiply that by Avogadro's number to find the energy change for a whole mole of oxygen nuclei, a mere 16 grams of oxygen, we get an amazing 1.23×10^{13} joules of energy. To produce that energy with coal, you would have to burn 420,000 kilograms, 420 metric tonnes of coal.

===== Nuclear Energy =====

That energy is what we mean when we talk about nuclear energy, the binding energy that's released when a nucleon is removed from its nucleus. Now, to dislodge one of those nucleons and unleash that energy there are two general types of nuclear reactions: fission and fusion.

Fission occurs when a large nucleus splits into two lighter ones. Fusion is the opposite when two light nuclei join together to form a heavier one. In both cases the products of the reactions are more stable than the starting materials, and this is, as always, what drives the reaction.

This is a graph of the binding energies of various elements compared to their mass numbers. Elements with very high binding energies such as iron-56 are very stable and rarely undergo nuclear reactions. But elements with lower binding energies can react much more readily. If the nucleus is heavier than iron 56 it will tend to break into two or more smaller nuclei; a fission reaction. If it's lighter than iron 56 it will more likely participate in a fusion reaction, joining two nuclei together to form a heavier one. But the most important thing to notice here, is that with both fission and fusion, stability increases as a result of the reaction.

Fission is the type of reaction that we use more often because it's the one that we're better at initiating and controlling, at least so far. And whether it's used in power plants or bombs, the most common fuel for fission is uranium-235. There are several ways that it can react, but the reaction is almost always triggered by hitting uranium with neutrons from another source. When that happens the uranium splits into smaller atoms. One such reaction produces krypton-92, yes krypton is a real thing, along with barium-141, three free neutrons and lots of energy. This energy is released mainly as the kinetic energy of the escaping particles which is immediately transferred to the surroundings as heat. Some energy is also released in the form of electro-magnetic radiation such as visible light, X-rays and gamma radiation.

===== Nuclear Power Plants and the Cons of Fission =====

Nuclear power plants use the energy released by these reactions to convert water to steam, which then is passed through turbines spinning a generator, powering cities and stuff. Because of the enormous amounts of energy these reactions can release nuclear power plants can potentially produce lots of electricity, but there's also, I think you may have heard, some serious draw backs.

For one thing, as you know, atoms rarely exist in isolation. We write the equation of a fission reaction as it fits just one atom, but in reality that one atom is surrounded by many, many more. And if one little neutron can trigger the reaction and that reaction liberates three more neutrons, well I think you can see where this is going. If the reaction isn't controlled each reaction trigger three more and every reaction releases the same amount of energy, which adds up fast. This is pretty much the definition of a chain reaction and it is the basis of the remarkable power of the nuclear weapon.

The same type of reaction occurs in nuclear power plants, but those reactions are controlled in several ways to keep them from getting out of hand. The fact is these chain reactions have the potential to produce far more heat than the plant can use, so much more that the temperature can easily rise to dangerous levels, enough to melt the uranium. This is the meltdown that you hear about and most reactor cores are immersed in water to disperse the heat and prevent this from happening. But that, that's not enough on its own to control this thing.

If the chain reaction is allowed to run freely, no amount of water can remove the heat fast enough to prevent a meltdown. A real way we control nuclear reactions is with control rods. They're made of materials that readily absorb neutrons and they're inserted between the fuel rods of uranium to slow the neutrons down and therefore slow the reaction. They can be put in more to slow the reaction more, and lifted out more if you need more heat.

===== Half-life and decay =====
Now the other sticky wicket of fission reactions is the stuff that's left behind. These reactions not only produce products that are still radioactive, they produce tonnes of them, lots of different troublesome kinds. Like we saw last week, uranium undergoes many different types of nuclear decay, so not only does each uranium atom produce isotopes of krypton and bromine, but that process also produces many other isotopes of other elements. And as these various nuclei break down they release more neutrons and more unstable products and the process continues for a long time.

All of these reactions eventually yield stable products but they have half-lives ranging from a few years to tens of millions of years. The products with shorter half-lives stabilize pretty quickly but they release particles and energy like crazy during that time so they're extra dangerous. The ones with longer half-lives decay more slowly, release less energy but that means it takes a very, very long time for them to stabilize. So long in fact, that for human purposes, it may as well be forever. That means they'll always be an issue in our environment which is why we're always looking for ways to store them, and keep them out of our way.

===== Fusion =====

Fusion reactions, as you'd expect, are very different from fission. For one thing, the energy released in many fusion reactions, dwarfs even the huge amount released by fission. You might be familiar, for example, with the wonderful work done by our sun.

The reactions that power the sun are like most fusion reactions in that they involve very small nuclei like isotopes of hydrogen and helium. This reaction begins when two atoms of hydrogen, accelerated by the sun's fantastically high temperatures and contained by its high pressures, join to form an atom of deuterium, an isotope of hydrogen. This fusion of particles releases a positron and some heat energy in the process.

Then another atom of hydrogen is joined to the deuterium to form helium-3. This step also releases a lot of energy in the form of gamma radiation. When two atoms of helium-3 are available they join together to form an atom of helium-4 as well as two atoms of regular hydrogen which then can be used to begin the process all over again. This final step also, as you might imagine, releases a large amount of energy in the form of mostly gamma radiation.

So this is a chain reaction too, but it's not a self-perpetuating one like we saw before. This reaction requires a total input of six atoms of hydrogen but it only produces two, in the end the remaining mass being released in the form of helium. For this reason more fuel is always needed, which is why our sun is going to run out of hydrogen in about five and a half billion years.

We can produce fusion reactions here on Earth too, but they're not very useful for us because we haven't figured out how to control them. They're super useful if you just want to blow up a big city though, just to be clear, depending on your definition of use. One reason is, as you can see on the mass-energy graph, light nuclei that fuse together undergo a much larger energy change than heavy nuclei that break apart. That means their reactions release far more energy than fission reactions do, so much more that it's nearly impossible to contain and therefore use.

Also, because fusion involves joining nuclei, the reaction has to overcome the really strong repulsion that naturally exists between their positive charges. For this reason, fusion reactions can only occur when particles collide at very high speeds or under very high pressures. At these mind-blowing speeds, the kinetic energy of the particles produces insane temperatures, like in the one hundred million kelvin range, at which point, the material being accelerated actually exists in the form of plasma.

So not only are those speeds really hard to reach but material at that temperature, how do you control that? Which is why we can't use fusion for things like generating electricity which would be super nice. We've only found applications for it when we don't need to control it at all like in nuclear weapons.

So as you can tell, there is plenty of room for new ideas in nuclear chemistry. Fusion would be really great because it would produce a lot of energy and you'd just get helium out of the process and helium is awesome! How can we use radioactive materials more efficiently? Is there a way to achieve the speeds and manage temperatures that come with fusion? And how can we do this stuff without blowing our faces off? You've already taken the first step by learning the basics. It's up to you how far you want to go from here. Maybe you'll write the next totally crazy ingenious and counter intuitive equation that takes us to the next level.

===== Ending =====

For now though, thank you for watching this episode of Crash Course Chemistry. If you paid attention, you learned how Einstein's famous formula helps us calculate the binding energy of a nucleus from its mass defect. You also learned the difference between fission and fusion, you saw an example of each one, and you learned about their applications in the real world. This episode of Crash Course Chemistry was written by Edi González and edited by Blake de Pastino. Our chemistry consultant is Dr. Heiko Langner. It was filmed, edited and directed by Nicholas Jenkins. Our script supervisor is Caitlin Hofmeister. Michael Aranda is our sound designer and our graphics team is Thought Café.