Orbitals: Crash Course Chemistry #25

Crash Course: Chemistry
https://youtube.com/watch?v=cPDptc0wUYI
https://nerdfighteria.info/v/cPDptc0wUYI

We spend a lot of time thinking about atoms as looking like this. There's a ball and there's a stick, and there's another ball and another stick. It's just a bunch of balls stuck together by these little wooden bonds. Simple. Pretty easy to understand, and thus—as you have probably come to expect—it is entirely incorrect.

Nuclei really can be understood as little balls, and that's more or less correct, though when you get to some of the bigger, less stable ones they start looking more oblong and weird like a rugby ball. Atoms are basically ball-like as well, with electrons and a spherical cloud around the nucleus.

But molecules, as we discussed last time, do not look like balls on sticks. Bonds don't form into neat little lines. They form from overlapping electron clouds or shells, flowing around the nuclei of bonded atoms. If you really get down there and understand what they look like, they're like lumpy, clumpy globs of probable electron locations. And these lumpy, clumps of probable electron locations do not behave the way you might initially expect them to behave. Oh no. That would be far too simple. They behave based on quantum mechanical, three-dimensional wave functions, probabilistic distributions of electrons in space. And yeah, by the end of this episode, you're going to understand what I just said and it's gonna be awesome!

[intro music]

=====Why is Water Crooked? (1:23)=====
Let's start with water, because all the interesting things on our planet start with water. It's also universally common, not just on our planet but in our galaxy and our universe. Case in point: In 2011, astronomers discovered a cloud of water-ice surrounding a black hole that contains 140 trillion times more water than we have here on Earth. And while we don't have any confirmed worlds covered in water outside of our solar system, we do have some right here in our solar system. Europa contains so much water, probably salt water, that its entire surface is just ice.

What did any of that have to do with atomic orbitals? Nothing. I just felt like maybe I scared you with all that quantum mechanics talk before the intro and I wanted to chill you out for a second.

Okay, so water. We did its Lewis structure last week, remember? Each hydrogen bonding to the oxygen atom, and voilà! But that drawing is linear, just a straight line through all the nuclei, and we know, just instinctually at this point, that water is a bent molecule.

But why? Why is water crooked? Unbonded atoms within a molecule generally like to be as far away from each other as possible, especially if they have the same partial charge as the two hydrogens do with their partial positives. But something is keeping those hydrogens closer together than they would like to be. So why on earth are they not stretched out as far away from each other as possible? I ask this because if they were, the water molecule wouldn't be polar, and if water was suddenly non-polar we would all instantly die, as would all life on Earth.

And suddenly, we realize that this seemingly normal thing that we knew about the world is really weird. And weird stuff is my favorite stuff because it means interesting questions. Interesting questions I want to know the answer to. It's an even more compelling question than, "What the heck is a quantum mechanical three-dimensional wave function?" Well, of course, the answer to this question has a great deal to do with quantum mechanical three-dimensional wave functions, so let's start there.

=====Electrons (3:12)=====

Oh, look! I've got a telephone cord! This is what old people used to use to get their voices into wires so they could be transmitted across the world before cell phones, but today it's pretty much only useful for demonstrating electron fields.

Electrons are both particles and waves, which is not an easy thing to imagine. Very basically, you can think of them as an excitation of the electron field, which exists everywhere.

When energy is dumped into the electron field, electrons exist inside a wave function. What's a wave function? It's a mathematical function that describes the probability that an electron is in a certain place at any given moment.

So, this telephone cord is an electron field. I dump some energy into it and we create what's called a standing wave. The wave function is the mathematical function that describes it.

=====Types of Orbitals (3:56)=====

Electrons function the same way. They exist as excitations in the electron field around the nucleus in a standing wave. The simplest of these wave functions is the s orbital, which can contain two electrons and is a spherical pattern of standing waves around the nucleus. This standing wave can have different numbers of nodes, allowing patterns to repeat themselves when there are more electrons around the nucleus.

Every orbital can contain, and indeed is at its lowest energy when it contains, two electrons. Hydrogen has one electron in its s orbital. Helium, an ultra-stable, very low-energy noble gas, has two. It's happy cause it has its shell filled.

But, of course, there are other sorts of orbitals as well. After we fill the first and second s orbitals, we move on to filling the p orbital. Or rather, I should say p orbitals, because we're talking about three dimensional space here, so there can be one on the x axis, and one on the y axis, and one on the z axis.

Each of those can contain two electrons for a total of eight with two in the s orbital and six in the three p orbitals. And yes, those eight electrons are the reason for whole the octet rule thing.

Remember now, the periodic table is a map of the orbitals as they fill. Elements in the s block are filling their s orbitals. Elements in the p block are filling their p's. Same with the d's and the f's.

So, s orbitals, very simple, spherical, p orbitals a little bit weirder, d and f orbitals, so crazy. Some of the f orbitals in particular have just ridiculously cool geometries. Lots of fancy math is involved in writing out these wave functions and understanding them.

=====Orbital Hybridization (5:22)=====

So, with hydrogen, we've just got the one s orbital. It's a sphere. Marvelously uncomplicated. But, in the second shell, we have an s orbital and three p orbitals. The p orbitals, if they were all by themselves, look like this. But, when you actually stick them around an atom, the s and p orbitals start to interact with each other, doing their best not to overlap and changing each other. The s and the p orbitals can merge into hybrid sp orbitals. Instead of being two different kinds of orbitals, they become four identical orbitals trying their best not to overlap.

This is called orbital hybridization. When the s orbital hybridizes with all three p orbitals it's called sp^3 [pronounced "s p three"] hybridization and it forms a tetrahedral shape.

And this is that tetrahedral shape. It's the easiest way for all the orbitals to form something like a sphere around the atom, but not interact too much. I didn't do anything fancy to make these balloons take this shape. I just tied them together at the base. They naturally formed this shape because they can't overlap with each other. And yes, this is exactly what's going on with water.

In water, oxygen's eight electrons are arranged with two in each sp^3 hybridized orbital. Two of those electrons are from hydrogen. Six are from oxygen, including two lone pairs. Those lone pairs, even though they're not participating in any bonds, still have their orbitals.

And so water is locked into that tetrahedral structure. No matter which orbital you stick the hydrogen atoms to, you're stuck with an asymmetrical molecule. That, along with the difference in electronegativities of oxygen and hydrogen, leads to the polarity of water and the existence of life.

But s and p orbitals can hybridize in other ways as well. How, for example, could you imagine sp^3 orbitals forming a double bond? You can't have two orbitals mashing together in the same space, and sp^3 orbitals are pretty much stuck in their tetrahedral structure.

Well, if a molecule is going to be at its lowest energy state by forming a double bond, it has a nice simple solution. It only hybridizes two p orbitals with the s orbital, forming three sp^2 hybridized orbitals with an unhybridized p orbital sticking up from the center. Tie balloons together like that, and you get what we call a trigonal plane. Each sp^2 orbital is 120° away from the other, drawing a line straight through their centers, and you get an equilateral triangle.

=====Sigma and Pi Bonds (7:32)=====

One of the two bonds in the double bond has sp^2 orbitals merging together nicely in line with the nuclei. This straightforward sort of bond is called a sigma bond. A second and weirder bond forms, this one from the unhybridized p orbital sticking out above and below the nucleus. These atoms merge to form a pi bond. That's your nice symmetrical double bond that you see in molecules like ethylene.

And, yes, sp orbitals, where the s only hybridizes with one p orbital, are also all over the place. These occur when an atom is either triple bonded to another atom or is double bonded to two atoms. The sp orbital, the one that forms the sigma bonds here, is linear. There are just two of them, balloons, easy, see? Straight line. The trick is to have those two unhybridized p orbitals that can engage in two pi bonds, either to form a single triple bond or to form two double bonds like in carbon dioxide.

=====Carbon Dioxide (8:23)=====

Carbon dioxide's orbital structure is actually really cool, so let's take a look at it as an example. The carbon is going to have two double bonds, so it has to have two un-hybridized p orbitals and one sp hybridized orbital. The oxygens are going to have one double bond, so they need to set up as sp^2 hybridized with one un-hybridized p orbital, for the double bonding.

As they come together for the bond, the sigma bonds will occur between the hybridized orbitals. Very simple. One oxygen will line up to form a pi bond with the vertically oriented p orbital from the carbon and the other will line up with the horizontally oriented one. There you have it. Bond, bond, bond, bond [on screen: animation of James Bond shooting a gun].

=====More Orbital Hybridization (8:56)=====

But, of course, as will always be the case in your unrelenting search for more knowledge, there is yet more to learn. d and f orbitals can hybridize with sp hybridized orbitals and with each other, forming some gorgeously peculiar geometries, and when two d orbitals hybridize with sp^3 orbitals, you get d^2sp^3, an octahedral structure, which those of you who play role playing games will recognize as an eight-sided die.

These orbital configurations determine the shape of molecules, and the shape of molecules determines how they behave, what forms they take, what properties they have. It's pretty dang amazing, really, that wave functions determining the probable locations of electrons keep water bent, and thus polar, and thus able to dissolve nutrients and form a stable home for ourselves so that we can walk around as weird bags of mostly water thinking about stuff, making YouTube videos, trying to learn more about the world, or maybe just trying to pass a test.

=====Conclusion and Credits (9:50)=====

Thanks for watching this episode of Crash Course Chemistry. If you were paying attention today, you learned that molecules are clumpy globs of probable electron locations determined by wave functions that are a bit more complicated than waves on a telephone cord, that water is an asymmetrical molecule because of oxygen's sp^3 hybridized orbitals forcing the electrons into a tetrahedral structure, and that s and p orbitals can also hybridize other ways as sp^2 or sp and how those hybridizations allow for double and triple bonds using both sigma and pi bond types. Finally, you learned that d orbitals can get involved too, allowing for hybridizations that form even cooler three-dimensional shapes.

This episode of Crash Course Chemistry was written by me and edited by Blake de Pastino, and our chemistry consultants are Dr. Heiko Langner and Edi Gonzales. It was filmed, edited, and directed by Nicholas Jenkins. Our sound designer is Michael Aranda, and our graphics team is Thought Café.