

Quantum Mechanics

You've probably already figured out that quantum mechanics is complicated. Many scientists prefer to say that it has an "elegant simplicity", but that's just because they're trying to convince people that they're smart. The truth is that nobody really understands what it all means, and we're all trying to wrap our brains about it.

This tutorial is kind of an introduction to get you started with understanding what quantum mechanics is. I'm not going to go into detail about the many equations that dictate it, nor will I try to blow your mind with a bunch of crazy facts. My only purpose with this particular tutorial is to help you to understand some of the very basic concepts.

And with that, let's start!

The pre-quantum world

Because there are already tutorials about the pre-quantum atom elsewhere on this website, I'll just touch on some of the main points of the pre-quantum world. It will provide the context you need to understand what's happening, but is probably not phrased in the same way as you've learned in class.

- Atoms are tiny balls: For most of human history, people have thought that atoms were basically little solid balls. Everything that happened with matter had to do with how these little balls stuck to other little balls. This idea originated with Greek philosophers and hung around until the late 19th century (thanks to Thomson).
 - Atoms have a lot of particles in them doing stuff: This is probably how you think about atoms, and there's something to be said for it. There's a nucleus with protons and neutrons and electrons that live outside of the nucleus in orbitals. Chemistry happens when these little particles do stuff. Which is true. Sort of.
 - Atoms are boring nuclei with cool electrons on the outside: This is the essence of the quantum model – that chemical changes happen not because of all the particles in an atom, but because the electrons rearrange in interesting ways. This isn't to say that the nucleus isn't present – it's just that we think a lot more about the electrons than the nucleus when doing chemistry stuff.
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So what's the deal with these electrons, anyway?

Some more history is needed here:

Niels Bohr came up with an equation that described the behavior of the electron in a hydrogen atom. This is unbelievably important because it tells us that electrons behave in ways that can be mathematically predicted. Let's see what this math looks like.

$$\frac{1}{\lambda} = R \left(\frac{1}{n^2} - \frac{1}{n'^2} \right)$$

You don't need to memorize this.

If you study this stuff long enough, this equation really turns out to have one variable: The distance at which the electron orbits around the nucleus. I know there are other symbols and letters, but that's the gist of it. One number and you're in good shape.

The only problem with this model is that it mostly doesn't work. It works for atoms that have one electron, but once you start adding more electrons (as is the case with everything but hydrogen), it starts throwing out nonsense. This tells us two things:

- Bohr is right! You *can* use math to predict what electrons do! After all, if the equation was complete nonsense, it wouldn't be effective at predicting anything at all!
- Bohr isn't finished yet! His math is a good start, but the assumptions violate some very basic principles about the universe. In other words, we've got to come up with a different equation.¹

Which is why quantum mechanics was invented.

What does quantum mechanics say?

I've touched on this point in other tutorials (most notably [here](#)), but I'll give a quick explanation for the sake of completeness.

Basically, electrons can be thought of as being some combination of a particle and a wave. In an atom, electron energies are very well known, so the electron behaves like a wave under these circumstance. It's like the way a guitar string moves – when you pluck the string, you can see the string vibrate like a wave, and the vibration is totally stable. Likewise, an electron in an atom is a three-dimensional wave that does the same thing. This is hard to imagine, so I recommend that you kind of go with it right now and wait until you've studied more about quantum mechanics in the future to get a clearer idea.

Because this wave is stable it can be expressed by a mathematical equation. This is called, straightforwardly enough, a wavefunction. This is, incidentally, the same thing that Bohr was trying to do with his one-variable equation. However, given the complexity of what electrons actually do, there are actually *four* variables that we need to take into account to describe what electrons actually do. These variables are called *quantum numbers*, and they give rise to all manner of awesomeness in the world of chemistry.

The four quantum numbers

There are, as mentioned above, four quantum numbers that are used to describe the characteristics of an electron. These are:

- *The principal quantum number, n* : The principal quantum number determines the energy level of the electron, and is the same variable that Bohr used when talking about atoms. The principle quantum number is allowed to have any counting value from 1 onwards (i.e. 1, 2, 3, ...etc.)
- *The angular momentum quantum number, ℓ* . (Note: The ℓ symbol is meant to be a lowercase L, but it comes out looking more like an e. Sorry 'bout that). The angular momentum quantum number determines the type of orbital an electron is in. For example, is

it an s-electron, p-electron, d-electron, or f-electron? An electron's ℓ tells us that. The angular momentum quantum number is allowed to have any counting value from 0 through $(n-1)$. To make this clearer, if $n = 4$, the angular momentum quantum number is allowed to be 0, 1, 2, and 3 ($3 = 4-1$, which is why we stop here).

- *The magnetic quantum number, m_ℓ* : (Note, this is an “m” with that weird little “l” under it, and is referred to as “m-sub-l” in conversation. Just as n tells us the energy level and ℓ tells us the type of orbital the electron is in, m_ℓ tells us *which* of the orbitals of that type is in. For example, there are three p-orbitals in an energy level, so the magnetic quantum number tells us *which* of these p-orbitals the electron is actually sitting in. The allowed values of m_ℓ are $-\ell, -\ell+1 \dots 0, 1, \dots \ell$). Or, to make this a little less annoying, if ℓ is equal to 1 (as is the case in a p-orbital), the possible values of m_ℓ are -1, 0, and 1. Conveniently, there are three possible values, which tells us that there are three p-orbitals!
- *The spin quantum number, m_s* . If you remember that it's possible to cram two electrons into an orbital, it may not be a surprise to learn that the spin quantum number allows us to tell them apart. The allowed values for m_s are $+1/2$ (spin up) and $-1/2$ (spin down). If the whole spin-up spin-down thing doesn't make sense, you may want to have a look at [this tutorial](#).

With these four variables, you can figure out the properties of any particular electron in an atom. And because the Pauli exclusion principle says that no two electrons in an atom can have the same four quantum numbers, knowing these four variables can help you to keep them apart.

OK... I'm confused about quantum numbers

Based on what I wrote above, you may or may not have any idea what I'm talking about. To make more sense of this, let's think of quantum numbers as addresses for electrons.

Let's say that we live in a country with the following properties:

- Everybody lives in a town. These are conveniently named 1, 2, 3, and so forth.
- Every house in the town is located on a numbered street. These streets have names that are based on the names of the town, such that the first street is named (oddly enough) “0”, the second street is named “1”, the third street is named “2” and so on. The names of these streets are based on the name of the town, such that the highest numbered street is one less than the number of the town. (So if you live in town 2, you'll have two streets, named “0” and “1”)
- We all live in some house on a numbered street. Each house is numbered, and the number of houses on a street is equal to $\pm$ the name of the street and every counting number in-between. For example, if you live on street “3”, there will be houses with the numbers -3 and +3, as well as every number in-between (-2, -1, 0, 1, 2). This means you'll have a total of seven houses on that street (-3, -2, -1, 0, 1, 2, 3).
- We all share a house with a friend, and we all have the name $+1/2$ or $-1/2$. If somebody wants to send mail to you, one occupant will be denoted with an address of $+1/2$, and the other will be denoted with an address of $-1/2$.

As a result, we can use four numbers to send a letter to anybody who lives in our country. If we were to address an envelope with the address: 2, 1, 1, $-1/2$, we'd be saying that we're sending a

letter to town 2, on street number 1, in house number 1, to occupant $-1/2$. That works out pretty well.

Now, let's say that we want to send a letter to the address 4, 4, 2, $+1/2$. The letter would be sent by the postal service to town 4, but because there's no street 4 in town 4 (they only go up to 3), the letter isn't allowed to pass. It goes right on back with an "Address not found" label.

In the same way, some values for electrons are allowed and some are not.

So, what have we learned?

Quantum numbers are variables that tells us four properties of electrons: Their energy levels (principal, n), the type of orbital they're in (angular momentum, ℓ), which of those orbitals it's in (magnetic, m_ℓ), and which electron it is within that orbital (spin, m_s). There is, of course, a lot more to know, but if you're aware of these, you should do fine with all the math you'll need to know for a while.

Footnotes:

1. This explanation of the Bohr model is a huge oversimplification of the shortcomings of the Bohr model, and is meant to give people a general idea of what's going on. For a much better explanation, click [here](#).