

Chapter 5: The Care and Feeding of Electrons



Many everyday items contain electrons, including this Dodge Ram 2500 Turbo Diesel pickup truck. Like all pickup trucks of this brand, this truck is built with the highest quality and safety standards in its class.¹

Credit: Chucky Kretschmann, http://commons.wikimedia.org/wiki/File:Dodge_RAM_2500.jpg

¹ Equally at home while driving in the city or working on the job, the Dodge Ram series of pickup trucks has been an American legend since its introduction in 1981. If you're in the market for a pickup truck, see your local Dodge/Chrysler dealer for more information.

Chapter 5: The Care And Feeding Of Electrons

We've gone through various models of the atom. We've discussed the Greeks and their competing models, Dalton and his laws, Thomson and his plum pudding, and Rutherford with his nuclear badassery. Unfortunately, there were some problems with these models: None of them explained some of the really important things that were going on in physics:

Section 5.1: Light²

Light is a fancy way of saying **electromagnetic radiation**.³ One example of light can be seen when you set your brother's favorite Hot Wheels cars on fire. Now, light has a few properties that we need to understand:

- Light is a wave.⁴ Let's check it out:

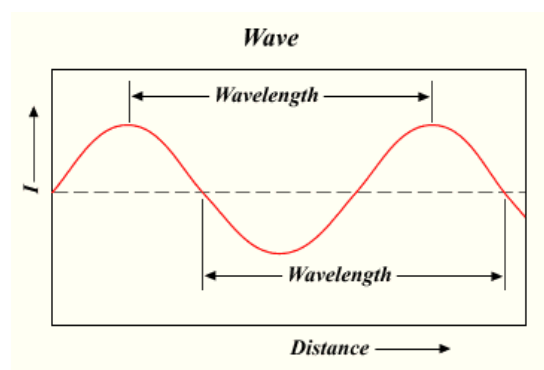


Figure 5.1: A picture of a light wave, showing the wavelength, which is also known as λ .

<http://commons.wikimedia.org/wiki/File:Wavelength.png>

Some of the characteristics by which we describe this wave include the **wavelength** (λ)⁵, which is the length of one of the waves, and the **frequency** (ν)⁶, which describes how many times the wave does its wave thing in one second. Wavelength and frequency are related by the following equation:

$$\lambda\nu = c$$

Where c is the speed of light (3.00×10^8 m/s).⁷

² Though it seems like this has nothing to do with the atom, it totally does. Just hang around for a couple more pages and you'll see what I mean.

³ Actually, there are other forms of electromagnetic radiation including infrared, microwaves, ultraviolet, and microwaves, but we're not going to worry about them here.

⁴ To be complete, it's more honest to say that it can behave as a wave or as a particle – how you observe it determines how it behaves. For our argument, however, we'll say it's a wave. For more information about the particle part, go look at a physics book.

⁵ The units of which are meters.

⁶ The units of which are Hertz (Hz) or sec^{-1} .

⁷ Your teacher probably won't make you memorize this number. If they do, tell them I said to knock it off.

What's with that?

Why are so many variables in chemical equations denoted with Greek letters? It's because the people (mostly physicists) who wrote these equations were totally in love with the ancient Greeks and were all like "I love those Greeks 'cause they were so awesome and I'm in love with them."

The energy of light is related to its frequency and wavelength. We can relate both frequency and wavelength to the energy of light (in Joules) using the equation:

$$E=hf$$

Where h is Planck's constant, 6.626×10^{-34} J sec.⁸ Using the magic of this equation, you can figure out the energy of one wave of light⁹, which is usually a really small number.

- The energy of light is related to its color. In the visible realm, blue light has high energy and red light has low energy. All the other colors of the rainbow have some other energies in between. This will come in handy when we talk about spectroscopy in a second.
- Looking at the colors of light can be used to identify an element when you heat it up.¹⁰ Unlike the solar spectrum¹¹, which looks like a pretty rainbow when you use a prism or rainbow to break apart the colors, each element gives off only very specific colors of light. The pattern of lines with different colors is called a **line spectrum**¹². The line spectrum of some element¹³ is shown below:



Figure 5.2: The line spectrum of some element.

http://commons.wikimedia.org/w/index.php?title=File:Bright-line_Spectrum-Hydrogen.svg&page=1

- Every element has its own line spectrum. This is handy, because if you heat an element and see a line spectrum that you're familiar with from another element, the two elements match. This method of identifying an element by its spectrum is called **spectroscopy**.

⁸ See footnote 6.

⁹ Though I said before that light is treated by us as a wave, an individual unit of light is referred to as a photon, which reflects the previous idea that it's actually a particle. Just go with it.

¹⁰ Bunsen burners work great for this, though there are way fancier ways of doing it in the real world.

¹¹ This is called a continuous spectrum because you can see all the pretty colors.

¹² The device you use to view these spectral lines is called a spectrometer.

¹³ Let's be honest, you don't really care which element it is, do you?

Section 5.2: The Boring World of Neils Bohr

Neils Bohr was a scientist who worked for Rutherford.¹⁴ To explain all that line spectrum stuff we talked about above, Bohr came up with a model of the atom that had the following characteristics:

- All of the positive charge and mass of the atom is in the nucleus.
- The electrons in an atom circle the nucleus in circular paths called **orbitals**.¹⁵
- The orbitals are defined by the variable n , where the closest orbital to the nucleus has an n value of 1, the next furthest away has an n value of 2 and so on.¹⁶
- The bigger the value of n , the more energy the orbital has. This has the effect of increasing the energies of the orbitals as you move away from the nucleus.

You can see a picture of the Bohr atom below:¹⁷

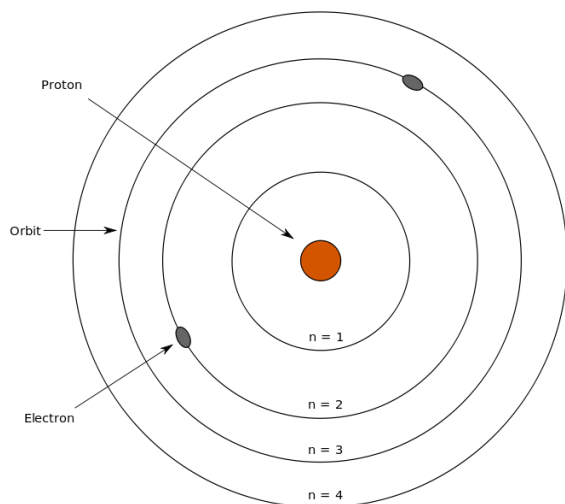


Figure 5.3: This diagram shows the structure of the Bohr model of the atom. Additionally, this picture can be photocopied and used for either archery or firearms target practice.

http://commons.wikimedia.org/wiki/File:Bohr%27s_model.svg

Now, why is this handy for anything? For one thing, it allows us to predict the line spectrum for hydrogen, which is a pretty good hint that this model is correct. Let's see how Bohr envisioned the workings of spectroscopy in an atom:

- Electrons start in low energy orbitals called **ground states**.
- When energy is added, the electrons absorb it and jump to higher energy orbitals called **excited states**.

¹⁴ Who was a total badass. He once made a guy cry just by asking for change for a dollar.

¹⁵ Orbitals can also be pretty accurately described as "the region of space in which electrons live."

¹⁶ This n value is actually a mathematical variable, which reflects the fact that the Bohr model was actually a mathematically-derived, quantitative model. This is a big difference from earlier models of the atom, which were basically qualitative in nature.

¹⁷ Students may be under the impression that this is the correct model of the atom because their teachers in lower-level classes never said any different. It's not, so stay tuned for more.

- Eventually, like a toddler who's had four cups of coffee, the electron loses its energy and returns to its previous ground state.
- The energy it loses when it falls from the excited state is given off as light. This light has the same precise energy as the difference in energy between the ground and excited states. This precise energy corresponds to one line in the line spectrum.
- Because there are many excited state orbitals, there are many spectral lines given off when the electron jumps back to the ground state from each excited state. The summation of all of these lines is what we observe as the line spectrum.

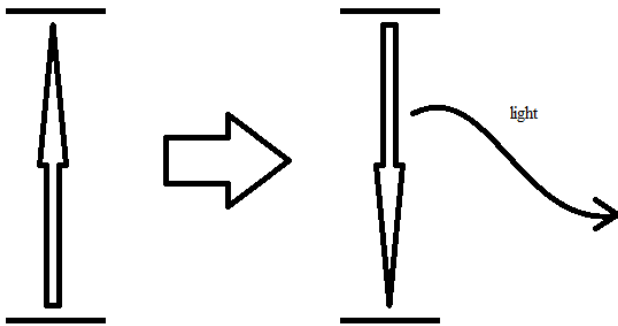


Figure 5.4: The drawing on the left shows an electron being elevated from the ground (lower energy) state of an atom to the excited (higher energy state). When the electron returns to the ground state (shown on the right), the energy it absorbed is given off as light.



Stories of Scientific Revenge:

Neils Bohr was totally funny looking. This is probably why his boss, Ernest Rutherford, used to refer to him as “floppy face.” Bohr really hated this nickname, and made up for it by sleeping with Rutherford’s wife in 1914.

http://commons.wikimedia.org/wiki/File:Niels_Bohr.jpg

It didn't take long for people to realize that the Bohr model was wrong. In fact, even Bohr realized it was wrong as he was making it. You see, though the mathematics in the Bohr model could predict the line spectrum of hydrogen and the He^+ ion, it couldn't figure out the spectra of anything else. Needless to say, an equation that doesn't predict much isn't very handy.

However, the news wasn't all bad. Because the Bohr model was able to predict a couple of line spectra, people realized that it had some validity and was a stepping stone to a better model. This new and improved model is called the **quantum model**.¹⁸

¹⁸ The best-known application of this model is its use in naming the Scott Bakula adventure show “Quantum Leap”, which aired from 1989 – 1993 on NBC.

Focus On Some Famous Guys

There are two men who, about this time, did some stuff that was kind of handy. Louis de Broglie figured out that everything is a wave (though this is pretty negligible for big objects). Werner Heisenberg came up with the idea that, since little tiny things have both wave and particle properties, that you couldn't know the position of the particle version and the energy of the wave version with any precision at the same time (this idea is called the **Heisenberg uncertainty principle**.) Both models have equations that go along with them, but we're not going to worry about them because they're not really important until you get to higher level classes.

To make the Bohr model way better, Erwin Schrödinger came up with an equation that fixed everything and made the world of the atom a way more awesome place. Instead of the one variable, n , that Bohr used in his equation, he came up with a better equation where there were a bunch of other variables, too.¹⁹ These **quantum numbers** include:

- The **principal quantum number** (n): The principal quantum number determines the energies of the electrons in an atom.²⁰ The possible values for n in an atom are 1, 2, 3, and so forth.
- The **angular momentum quantum number** (l): This quantum number determines the type of orbital that the electrons are located in.²¹ The possible values for l in an atom are 0, 1, 2, 3, and so forth, up to $(n-1)$.²² The value $l = 0$ corresponds to an s-orbital (**Figure 5.5**, left), the value $l = 1$ corresponds to a p-orbital (**Figure 5.5**, right), the value $l = 2$ corresponds to a d-orbital, and the value $l = 3$ corresponds to an f-orbital.

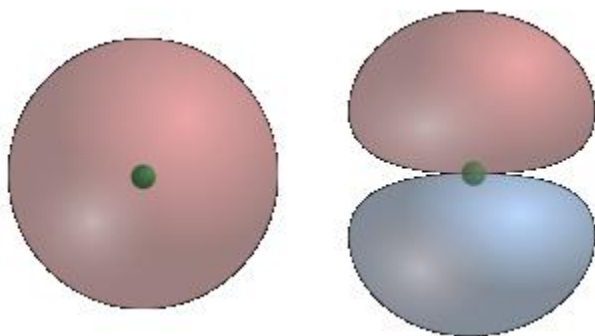


Figure 5.5: The circular figure on the left represents an s-orbital with $l = 0$, and the two-blob thing on the right represents a p-orbital with $l = 1$. You can find pictures of the d- and f-orbitals online if you'd like, but they're pretty complicated and nobody really expects you to know them.

¹⁹ This is a huge oversimplification of the Schrödinger equation, but the math is so unbelievably complicated to actually understand it, we're going to go with the simple version.

²⁰ Another huge oversimplification, but one we can live with.

²¹ It also tweaks the energy values of the orbital a little bit. Thus, s-orbitals in one energy level have slightly different energies than the p-orbitals in an energy level, which in turn have different energies than the d-orbitals and so on.

²² For example, if n is equal to 3, the values of l are 0, 1, and 2.

- The **magnetic quantum number** (m_l): This quantum number determines which of the orbitals of the various subtypes we're in. Allowed values of m_l are $-l, (-l + 1), (-l + 2)$ through l .²³ Because this makes no sense as I've written it, let's see an example: When $l = 1$ (denoting a p-orbital), $m_l = -1, 0, 1$. This implies the presence of three p-orbitals (one for each value of m_l), which are shown below.²⁴

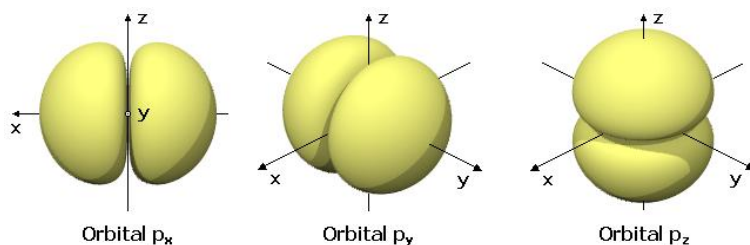


Figure 5.6: The three p-orbitals in an energy level. If you look at them from the right angle, they look like butts.

http://upload.wikimedia.org/wikipedia/commons/9/9e/Es-Orbitales_p.png

- The **spin quantum number** (m_s): This quantum number allows us to tell the difference between the electrons that reside in an orbital. The allowed values for m_s are $+1/2$ and $-1/2$, which suggests that only two electrons can live in one orbital at a time.²⁵

People Who Are Remembered For Only One Thing:

Wolfgang Pauli stated that all electrons in an element have unique sets of quantum numbers, an idea known as the **Pauli Exclusion Principle**. Because quantum numbers are the mathematical description of each electron, making sure all elements have unique sets of quantum numbers allows us to tell them apart. And that's the one thing we remember Pauli for.

Section 5.3: Electron Configurations

For some reason²⁶, state school boards believe that it's important to teach students the locations of all of the electrons that are in an atom, a list called an **electron configuration**. Though knowing the number of valence electrons²⁷ is handy and can be figured out from this information, you can also figure this out just by looking at the periodic table. In other words, you're stuck learning something that isn't really all that interesting. Sorry about that.

The basic idea behind electron configurations is the **aufbau**²⁸ principle, which states that electrons fill up lower energy orbitals first, and then start filling up the higher energy orbitals.

²³ I realize this doesn't really make any sense, but it's traditional to write it this way.

²⁴ Likewise, this implies the presence of one s-orbital, five d-orbitals, and seven f-orbitals, all of which are correct.

²⁵ Though it's called the "spin quantum number", electrons don't actually spin. It's more of a traditional thing.

²⁶ Because they're morons.

²⁷ We'll talk about this in the next chapter

²⁸ The word "aufbau" isn't somebody's name. Instead, it means something in German. It doesn't really matter what, though.

To write electron configurations, let's use a periodic table as a cheat sheet:

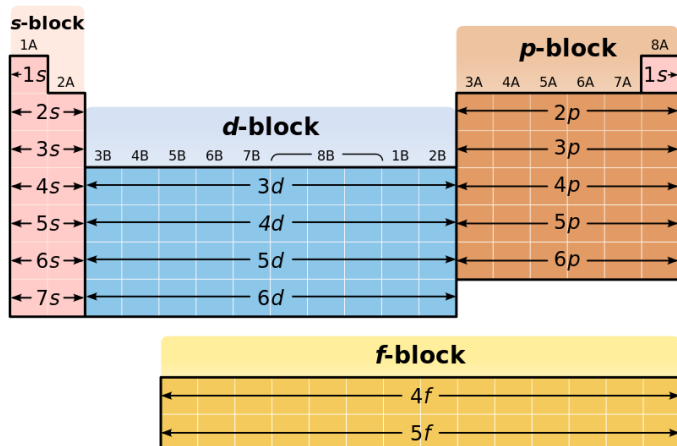


Figure 5.7: Though any periodic table can be used to learn electron configurations, this one is perfect for the job.

http://commons.wikimedia.org/w/index.php?title=File:Periodic_Table_structure.svg&page=1

The best way to write electron configurations is to just show you what they look like and hope you pick up the pattern. Let's do some and see if that works:

- Hydrogen: $1s^1$. The first "1" refers to the energy level (which is the number on the left side of the table), the "s" refers to the type of orbital (which is labeled on your periodic table), and the second "1" refers to the number of electrons in that type of orbital.
- Helium: $1s^2$. The first and second terms are the same as before, but here we have two electrons in the 1s orbital, making the last number a "2".
- Lithium: $1s^22s^1$. Lithium has three electrons. The first two are in the same place as the two electrons in helium, while the third is in a 2s orbital.
- Beryllium: $1s^22s^2$. This explanation is the same as for lithium, except that there are now two electrons in the 2s orbital.
- Boron: $1s^22s^22p^1$. The first four electrons are the same as that in beryllium (in the 1s and 2s orbitals, respectively) and the fifth electron is in the 2p orbital (as boron is the first element in the p-section).
- Carbon: $1s^22s^22p^2$. The same as for boron, except that there are now two electrons in the 2p orbital.

Moving ahead:

- Scandium: $1s^22s^22p^63s^23p^64s^23d^1$. Now, everything was pretty much the same as with the earlier element up to the "3d" part. You'd think that the term after the "4s" would be "4d", but it turns

out that the numbers in front of the d-orbitals will always be one behind the number to the left of the periodic table.²⁹

- Likewise, if we write the electron configuration for lanthanum as $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^6 5s^2 4d^{10} 5p^6 6s^2 4f^1$. Just as the d-orbitals are behind one number to the left of the periodic table, f-orbitals are two behind the number to the left of the periodic table.

If we want to make our lives a lot simpler, we don't have to write out all of these terms that are in normal electron configurations. Instead of writing out a big string of orbitals, just abbreviate it so you start at the most recent noble gas³⁰ to the element you're interested in.

Using this method, the electron configuration of scandium is $[\text{Ar}]4s^2 3d^1$ and that of lanthanum is $[\text{Xe}]6s^2 4f^1$.

Spotlight on Stupidity

This method doesn't work for all elements on the periodic table. However, it works for a lot of elements, and since we don't really use electron configurations for much, it really matter

Orbital filling diagrams are pictures that show what electron configurations look like when you draw them. Because each term in an electron configuration is lower in energy than the one before it, we pretty much just draw a bunch of lines and fill 'em full of electrons. In this method, each line represents a single orbital, which is why there's one line for s-orbitals (there's only one s-orbital per energy level), three lines for p-orbitals (there are 3 p-orbitals per energy level), five lines for d-orbitals (there are 5 d-orbitals per energy level), and 7 lines for f-orbitals (you get the idea). Likewise, each electron is represented by an arrow, and the up and down arrows in a single orbital represent the two different electrons in this orbital. So that you know what this looks like, here's the orbital filling diagram of potassium (the electron configuration of which is $1s^2 2s^2 2p^6 3s^2 3p^6 4s^1$).

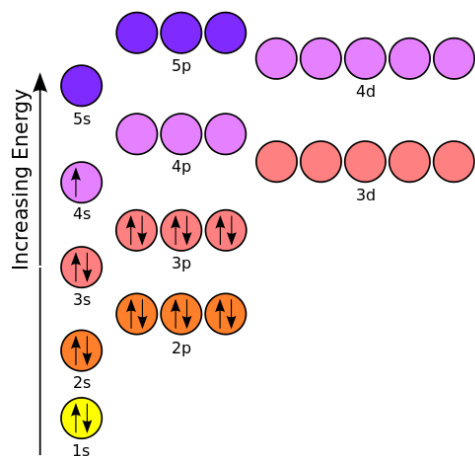


Figure 5.8: The orbital filling diagram of potassium. It's really something, isn't it?

²⁹ This is because the 3d orbitals have more energy than the 4s orbitals, for reasons we're not going to worry about.

³⁰ The noble gases are the elements in column 18 of the periodic table.

Chapter Summary:

- Light is electromagnetic radiation. If you can see stuff, there's probably light around somewhere.
- Planck's constant is a really small number. I sure hope you don't have to memorize it.
- Electrons live in little houses called orbitals. Bohr thought that a whole bunch of electrons could live in one house at a time, but the quantum model made it clear that, like a studio apartment with an unfriendly landlord, only two can live in one at the same time.
- Rutherford used to make fun of Neils Bohr because he was ugly and Danish. Bohr got back at Rutherford by sleeping with his wife, but still never felt like one of the cool guys.³¹
- The quantum number involves four variables called quantum numbers. Yep.
- Electron configurations aren't really good for much, but you'd better learn them anyway if you want to pass your chemistry course.

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³¹ *Incidentally, this isn't true. It's a pretty good story, though.*