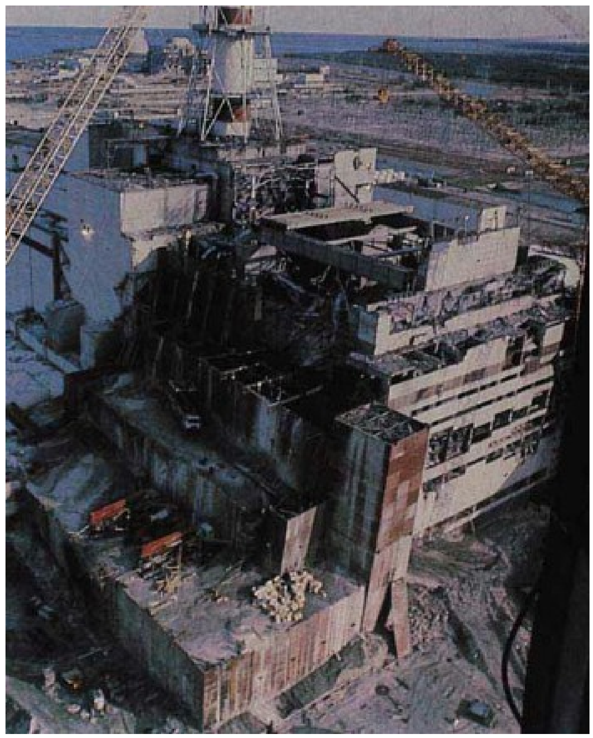
Chapter 4

Atoms: Our Very Tiny Friends



When atoms have a big party, this is the sort of thing that can happen.

4.1: The History of the Atom

Atoms are small. Not just kind of small, but really, unimaginably small. They're so small that if you were to expand the size of a car by fifty, you'd still totally be like “Wow, that atom is really small.” It's because of this smallness that people had a hard time figuring out what atoms are like. Let's see how our ancestors figured it out.

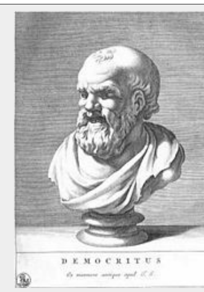
The Greeks

Ancient Greeks thought about a lot of stuff, including the stuff that matter was made of. Unfortunately, they didn't have much to go on, so didn't always make the best guesses.

- Leucippus: In the 5^{th} century BC, Leucippus came up with the idea of atoms. Though he had absolutely no experimental data, Leucippus came up with the idea that small particles called atoms make up all of matter, and that the shape and size of these atoms determines their properties.

Don't You Mean Democritus?

Most textbooks give credit for atomism to Democritus and not Leucippus. Democritus was Leucippus' student and since none of them wrote anything down, they're both usually given credit for the theory of atomism. Even though Leucippus totally came up with it.



This is what Democritus would look like if you sawed off his head.

- Plato (427-327 BC): Plato believed there were four elements (earth, air, fire, water), and each element corresponded to a different geometric shape.

- Aristotle (384-322 BC): He said that atoms didn't exist and attributed the nature of matter to being one of substance and essence. Because this explanation leaves the realm of science and enters the world of metaphysics, we'll just move on.

And so mankind lived for about 2,000 years, believing that Aristotle was right and that atoms didn't exist. Still, given that mankind did way worse stuff over that time than misunderstand the atom, we can probably overlook this.

Dalton: Bringing Back Atomic Theory

It wasn't until 1805 that English scientist John Dalton came up with a convincing new argument for atomic theory. People had started believing in atomic theory in the 16^{th} and 17^{th} centuries, but it took until the early 19^{th} century for Dalton to come up with the needed data to make a really convincing case. Here's what he said:

- Everything is made of indestructible, tiny atoms.
- Atoms of the same element have the same properties, while atoms of different elements have different properties.
- Atoms form chemical compounds by combining in whole-number ratios.
- Chemical compounds always have the same formulas, no matter how they're made.[1]

These laws may seem pretty ordinary to you, but back in the day they were pretty cool stuff. For example, they couldn't actually see that matter is made of atoms. The idea of different elements having different properties is also pretty bold for people who hadn't yet invented the periodic table. And don't even get me started on the “chemical compounds always have the same formulas” thing, because the presence of impurities in chemical samples usually makes it look like this isn't true.. Dalton took a bunch of ideas that were bouncing around and developed a really useful and modern atomic theory from them.

Let's Pull Out Those Eyes!

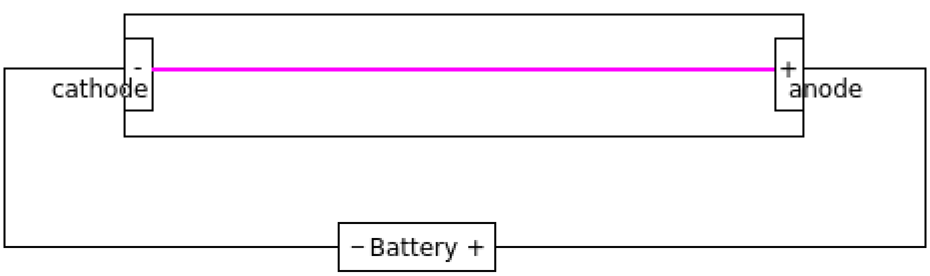
John Dalton was one of the first to characterize color-blindness, as he suffered from deutaneropia. Upon his death he ordered doctors to study his eyeballs and see if the wet mushy stuff inside was tinted, causing his color-blindness. They found nothing interesting but saved his eyes in a dish, just for fun. In 1995, DNA testing on these dried out eyeballs showed that Dalton was, indeed, colorblind. Which he could have told them 150 years earlier.

This model of an eyeball from the 1600's is creepy as hell.

Thomson's Plum Pudding Model

Until around the start of the 20th century, everybody was cool with the idea of Dalton's atom. However, things were to change when Englishman Joseph John (J.J.) Thomson did some experiments with cathode rays.

In 1897 Thomson was messing around with something called a cathode ray tube. It looked a lot like this:

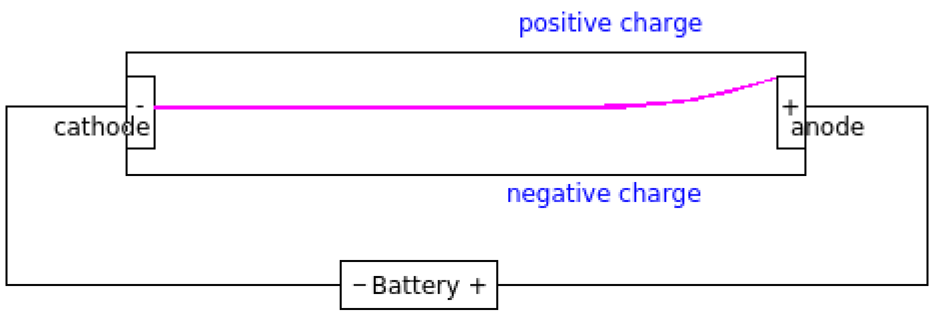


1 *This was actually come up with by Joseph Proust, but it was a part of the whole atomic theory thing.*

In his experiment, Thomson hooked up a battery to an empty glass tube. On the inside of the tube were two electrodes: The cathode, which has a negative charge; and the anode, which has a positive charge. When Thomson plugged the whole thing in, he saw a beam of light traveling across the tube.[2]

This didn't make much sense. On the one hand, the beam couldn't be caused by moving atoms because the electrodes didn't appear to be eroding away. On the other hand, it couldn't be caused by particles smaller than atoms because nothing was thought to be smaller than an atom. Weird.

Fortunately for us, Thomson kept experimenting. When he placed some magnets near the tube, he saw the following:



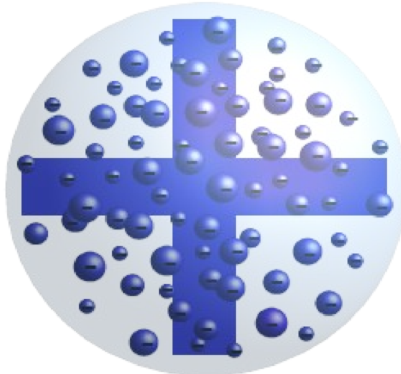
When he placed a positive charge above the tube and a negative charge below it, the beam turned toward the positive charge. From the fact that this beam bent away from the negative charge and toward the positive charge, he deduced that it must have negative particles in it (after all, positive attracts negative).

Left with this confusing stuff, he came up with the following conclusions about the atom:

- The atom *does* contain smaller particles that can be knocked out with electricity.
- These particles have negative charge, since they are repelled from the negative charge and attracted toward the positive charge.
- The positive stuff in the atom must be a lot bigger and heavier than the electrons, or else they'd move around, too.

2 *It's shown as purple here because I've been unable to find a reliable source for the actual color. With no other information, I decided to go with the one I found most aesthetically pleasing.*

From this, he devised the plum pudding model of the atom:



Atoms consist of a big blob of positive charge, into which are embedded small negative charges that can be pulled out.

In the plum pudding model, the vast majority of the atom's size and mass consists of positive charge. Embedded into this ball of positive charge are a bunch of very light negative particles (which we now know as electrons). It was called the plum pudding model after a doughy English Christmas containing raisins.[3]

Plum Pudding (model) vs. Plum Pudding (food)

Plum Pudding (model)	Plum Pudding (food)
Inedible	Edible but not tasty
Explains results of cathode ray tube experiment.	Explains why English people have bad teeth.
Very, very small.	Not as small as you'd probably like.
Discredited shortly after its discovery.	Still being consumed today.

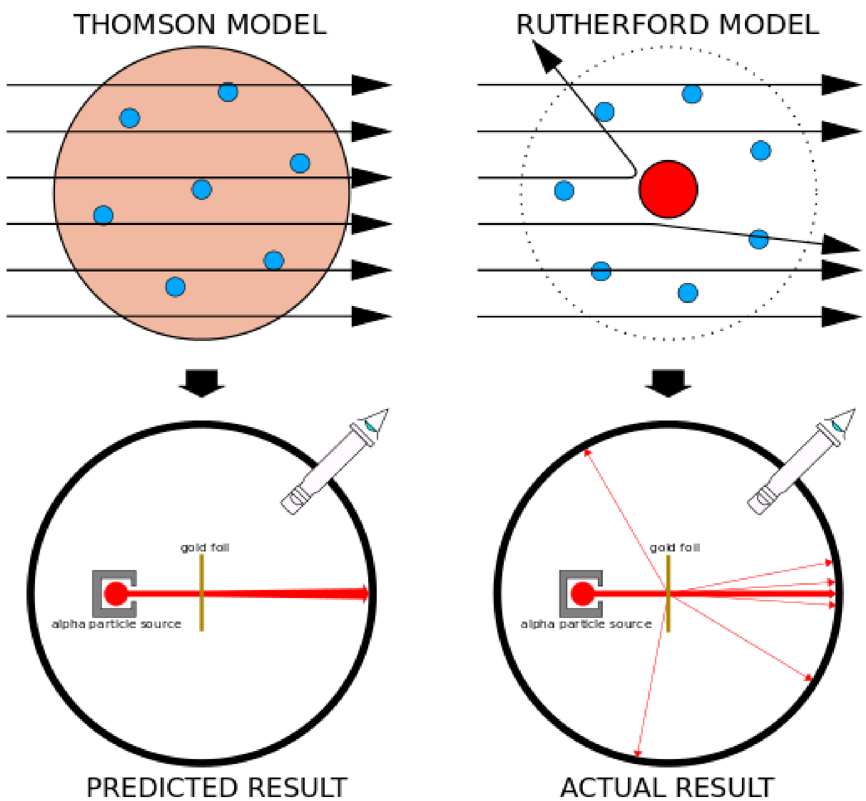
Rutherford Plays With Gold Foil

Way back in 1908, a guy named Ernest Rutherford was messing with α-particles (pronounced “alpha particles”) which he already knew were positively-charged particles given off during the radioactive decay of atoms. His goal was to figure out how many alpha particles were given off during radioactive decay. Rutherford was really into radioactive decay, to put it mildly.

To figure out a better way to count these alpha particles, Rutherford put his buddy Hans Geiger and Geiger's undergrad lackey Ernest Marsden to work. Fortunately for all of us, both Geiger and Marsden were unbelievably smart and devised the **Geiger-Marsden experiment,** which is also commonly called the **“gold-foil experiment.”**[4]

3 *Despite the name, plum pudding actually contains raisins and not plums.. Which is still gross.*
4 *Rutherford usually gets credit for this experiment, though he didn't actually design it. However, when Rutherford crunched the data later on, he was the guy who figured out what it really meant. Which we'll discuss shortly.*

In this experiment, alpha particles from the decay of radium atoms were fired at a very thin sheet of fold foil. Given that the Plum Pudding model predicted that atoms were little balls of stuff, everybody just kind of figured that the particles would just blast right through the gold foil, as seen below.[5]



In reality, things were different. Most of the particles passed through the foil, but a few of them scattered all over the place, and in some cases even bounced backwards. Based on this, Rutherford proposed that the positive charge in an atom is concentrated into a very small nucleus. Given this model, the experimental data can be interpreted in the following way:

- Most of the particles passed straight through the gold foil because atoms are mostly empty space. The alpha particles don't have much trouble passing through empty space, because, well, it's empty.

- Even though the nucleus is really small, the sheer number of positively-charged alpha particles that passed through the gold foil ensured that some of them would come near one of the nuclei. When this happens, the positive charge of the nucleus and the positive charge of the alpha particles repelled, causing some of them to veer away at strange angles.

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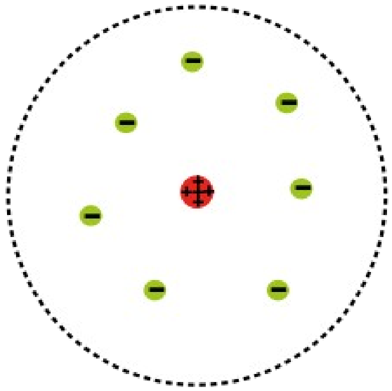
5 *You may wonder why anybody would think that the alpha particles would pass through a solid object like gold foil. Alpha particles are, in fact, stopped by very thin objects such as sheets of paper, but gold foil is unusual because it's really, really thin (~10^{-7} m – put another way, 1,000 sheets of gold foil are as thick as a single sheet of paper).*

From this, we get the **Rutherford model of the atom**:



The Rutherford model describes the atom in the following way:

- **The positive charge and mass of the atom are concentrated in the central nucleus**. The positive charge stuff was pretty well established by the gold foil experiment, and the fact that only electrons could be knocked off of atoms in the cathode ray experiment suggests that the nucleus was way bigger than the electrons.
- **The negative charge exists in little particles (electrons) that hang out around the nucleus**. There really wasn't any evidence about how they might be set up, so it was just kind of assumed they were just wandering somewhere around the nucleus.
- **The atom is spherical**. Considering that the electrons had negative charge and the nucleus had positive charge, it makes sense that they'd hang around it in a round ball.

Spotlight on Badassery: Ernest Rutherford

By the time Ernest Rutherford came up with his nuclear model of the atom, he had already won a Nobel Prize for describing the half-lives of radioactive elements. During World War I, Rutherford helped to develop sonar technology, and in his later years he predicted the existence of the neutron. Unfortunately, Rutherford's common sense wasn't as well-developed as his intelligence, as he died of complications related to an untreated hernia in 1937.

If you suspect you have a hernia, see a doctor immediately.

4.2: The Stuff in An Atom – Subatomic Particles

With the Rutherford model of the atom, we started getting a pretty good idea of what kinds of little things are sitting around inside of an atom. Let's learn what they are:[6]

	Proton (p^+)	Neutron (n^o)	Electron (e^-)
Charge	+1	0	-1
Where it lives	nucleus at center of the atom	nucleus at center of the atom	orbitals outside the nucleus
How much it weighs (kg)	~10^{-24} kg	~10^{-24} kg	~10^{-27} kg
How much it weighs (u)	~1	~1	~0[7]
size (m)	~10^{-15} m	~10^{-15} m	it's complicated[8]

Atomic Mass and Atomic Number

Some of the characteristics we care about when talking about atoms are their masses and their atomic numbers.

The **atomic number** of an atom is the number of protons that exist in the atom's nucleus. It is the atomic number of an atom that defines what element you've got. For example, all atoms with one proton in the nucleus are atoms are hydrogen, while those with two protons are helium atoms, those with three are lithium atoms, and so forth. You can find all of these numbers in the periodic table if you're curious.

How to read the boxes on the periodic table:

The top number in the periodic table (in this case, the 47) is the atomic number of the element (also the number of protons in this element). The symbol in the middle is the atomic symbol, which tells you what element it is (Ag is silver). The number at the bottom of the box is the average atomic mass of the element in u. *I'll get to that in a minute.*

47
Ag
107.87

6 *Let's be honest, you already know about protons, neutrons, and electrons. However, it's traditional to pretend that they're new, even though you've been taking science classes for years and years.*

7 *The amu is a unit that's used to describe the masses of subatomic particles. The mass of an electron is 1/1836 that of a proton, or 1/1823 of an amu.*

8 *It has to do with quantum mechanics and is more complicated than we can really go into here. However, I didn't want to lie to you and give a fake answer so I just said "it's complicated."*

The **atomic mass**[9] of an element is equal to, well, the mass of one atom of an element (given in unified atomic mass units, abbreviated either as *u* or *amu*)[10]. We usually consider the atomic mass of an element to be equal to the number of protons plus the number of neutrons in the atom, so an atom with five protons and six neutrons would have an atomic mass of 11.

It's going to get a little weird here for a minute, so hang with me.

Every element has several forms that can exist. This occurs because, while every element can have only one number of protons (hydrogen = 1, helium = 2, etc.) they can also exist with different numbers of neutrons. These different forms of the element are referred to as **isotopes**. In the case of carbon-14, there are six protons (because all carbon atoms have six protons) and eight neutrons (because 6 protons + 8 neutrons = 14). The mass of an isotope of an element is measured in u.

What aren't you telling me?

Well, I'm not exactly telling the truth about the masses of stuff. For example, carbon-14 doesn't weigh exactly 14 u. Instead, it weighs 14.003241 u because of, you guessed, it quantum effects. However, it's conventional to give the isotopes whole-number names like carbon-14 or uranium-238 because they're close enough for anything we need to worry about.

Apparently somebody got an advance copy of this book.

That said, it's time to get to the idea of the **average atomic mass** of an element. The average atomic mass of an element is a *weighted average of the isotopic masses*. As an example, hydrogen has three isotopes: Hydrogen-1, hydrogen-2, and hydrogen-3. The overall average atomic mass of hydrogen, 1.008 u, reflects the fact that most of these atoms have a mass of 1 u. This is the number that's at the bottom of the box on the periodic table – 107.87 for silver in the example above.

4.4: Modern Models of the Atom

Now that you've learned a bunch of models of the atom from a long, long time ago, it's time to start learning about the models we actually use these days. After all, if you just learn about the old stuff, people will wonder why you're so fixated on plum pudding.

With that, let's learn some of the good stuff.

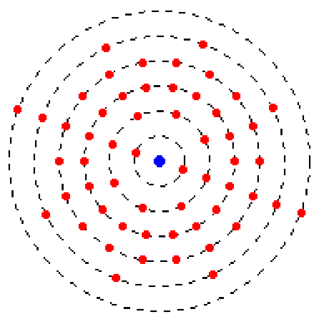
9 *Also called "mass number" or "atomic mass number", just because.*
10 *The use of amu reflects the fact that these units used to be called atomic mass units. Technically, amu isn't in use anymore, but it's used very widely and I tend to use it, too. Officially, the units that should be used are either unified atomic mass units (u) or daltons (Da).*

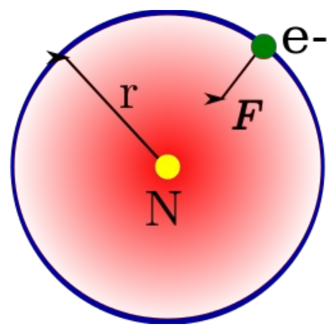
> ***Modern Models of the Atom***
>
> *It's important when reading this section to keep in mind what we're talking about when we say that we have a "model" of something. Instead of thinking of a model as reality, models actually serve to represent real things in a way that makes them comprehensible. In this sense, keep in mind that the modern atomic models are just that – models. They're theoretical constructs that are used to help us understand the very, very complex nature of reality. It's entirely possible that we'll come up with better models in the future, but this is pretty much what we're stuck with now.*

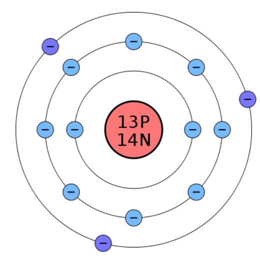
The Bohr Planetary Model of the Atom

The **Bohr mode**l of the atom represents an atom as having a positively-charged nucleus that contains both protons and neutrons, while electrons orbit around the nucleus in the same way that planets orbit the sun. A few pictures of this model of the atom:

What Bohr said:







There are a few features of the Bohr model that make it interesting and useful:

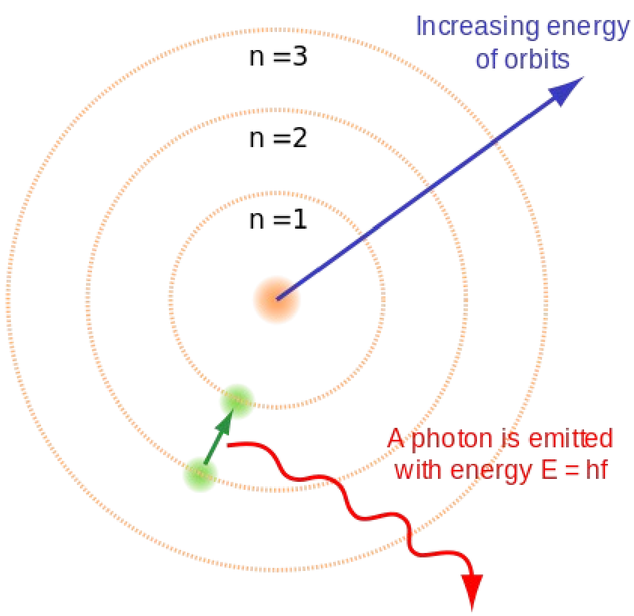
- **The Bohr model accepts the idea of the nucleus**. The Bohr model describes the nucleus such that the positively-charged protons and neutral neutrons are located in the nucleus of the atom.

- **The Bohr model puts electrons in circular orbitals around the nucleus.** Just as the sun has planets circling around it, the Bohr model tells us that there are negatively-charged electrons orbit in a positively-charged nucleus.

- **The electrons in each orbital have different amounts of energy than the other orbitals.** Electrons in orbitals close to the nucleus have low energies, with energies increasing as they move away from the nucleus. This energy is related to the orbital's **principal quantum number**, which is denoted by the variable, n. The innermost orbital is defined as n = 1, the second closest is n = 2, and so forth.

- **The orbitals are all located at specific distances from the nucleus and can only exist at those specific distances**. This may seem a little strange, but consider standing on a ladder: You can only stand on the rungs, which only exist at certain distances from the ground.

- **Because orbitals are only found at certain distances from the nucleus, electrons can only have energies related to these particular distances**. Just as you can only fall from certain heights from the rungs of a ladder, the electrons in an atom can only have certain energies.

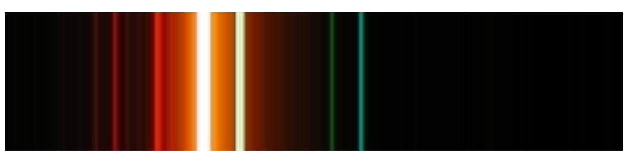


Like this, but with fewer words.

Best of all, this model of the atom actually had some mathematics to back it up. That principal quantum number I mentioned on the last page (and which is called "n" in the diagram above) is a variable in an equation that can be used to calculate the energies of electrons. You've probably already learned that scientists really like numbers, so the whole "it uses an equation" thing was a big hit among the nerdy crowd.

The question that might come to your mind[11] is "Why would Bohr ever have come up with something like this? What was wrong with the last model of the atom?"

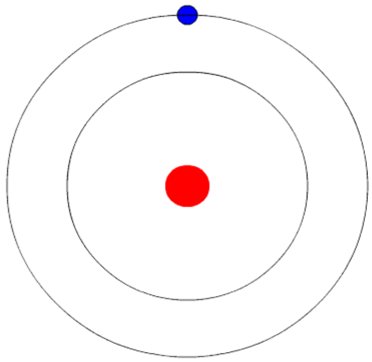
It turns out that there were some pretty weird observations going on around this time. If you heat up a piece of the element sodium, you get a nice yellow flame. However, if you use a prism to analyze each wavelength of this light, you get a picture that looks like this:



At first glance, this isn't particularly interesting. All it means is that when you heat up sodium, some colors of light are given off and some aren't. However, when you consider that the color of the light is related directly to the energy of the light, this means that if you heat sodium, there are only a few energies of light given off. The rest of the energies (i.e. everything aside from the colors of light in this picture) don't exist at all. Which is weird.

11 *But probably didn't.*

Bohr's model explains this by saying that when you add energy to an atom (like you would when heating it), this energy causes electrons to jump from lower energy orbitals to higher energy orbitals. When the electrons fall back down to their original orbitals, the energy they absorbed is given off as light. Because orbitals only have very particular energies, the light only has very particular energies.



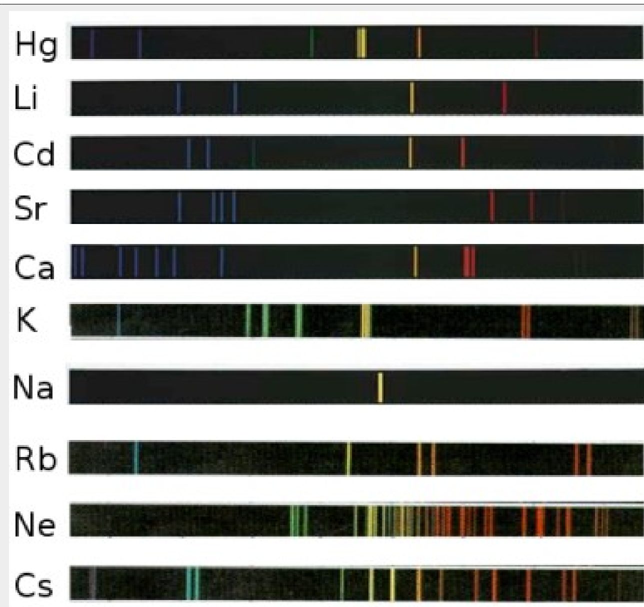
This animation does a good job of showing what happens when an atom absorbs and emits light. If you're reading this on paper or for whatever reason can't see the animation, visit https://commons.wikimedia.org/wiki/File:Bohr_atom_animation.gif.

This diagram shows the process by which this occurs. The wavy red line that bounces into the atom from the right represents light that hits the atom. When the electron in the lower energy level (called the **ground state**) near the nucleus absorbs this energy, it is promoted to a higher-energy orbital (called the **excited state**) farther from the nucleus. When the electron falls back to its original orbital, the energy that had earlier been absorbed is given off as light.

The coolest part: The color of light given off is equal to the energy difference between the low energy and high energy orbitals. That's why only certain colors of light are given off: Since orbitals only have certain energies, only certain energies of light are given off.

So what?

*Why would anybody care that elements give off particular colors of light? It turns out that every element has orbitals with unique energies, so each element gives off a unique pattern of light (called a **line spectrum**). As a result, if you don't know what element you've got sitting around in a bottle, you can heat it up and take a look at the spectrum of light given off to figure out what it is. The process in which spectra are used to identify unknown elements or compounds is called **spectroscopy**.*



A bunch of different atomic spectra

Niels Bohr: Idiot or Visionary?

There was only one problem with the Bohr model of the atom: It didn't work. I mean, sure, it helped make a lot of stuff about the atom clearer, and was a huge improvement over the Rutherford model. It even allowed scientists to figure out the energies of the electrons orbiting the nucleus. What could be better?

Well, it turns out that there was a minor snag in the Bohr model. Though it could, indeed, calculate the energies of electrons, it could only do so for atoms that contain one electron. Because most things in the universe are neither hydrogen atoms or helium ions, this had limited applications. Given this, it's easy to think that Niels Bohr was some kind of dumbass.

At this very moment, Einstein was wondering who let the dumbass in.

However, Niels Bohr turned out not to be a dumbass. In fact, he *knew* that the model of the atom named for him wasn't right. As soon as he came up with the math behind the model, he instantly knew it was flawed..

The reason he told people about the model anyway is that it was *kinda* right. It may not have predicted the energies of every electron in an atom, but it *was* able to predict the energies for atoms with one electron. It's not perfect, but it's not something that would happen by accident. Though Bohr was wrong, his results showed that he was on the right track.

Which is why Einstein and Bohr got along well. Mostly.

The Quantum Mechanical Model of the Atom

If you ask a normal person how to fix something that's broken, they'll try to simplify things until they work. If you ask a mathematician how to fix something that's broken, they'll keep adding more variables until things seem like they're working right.

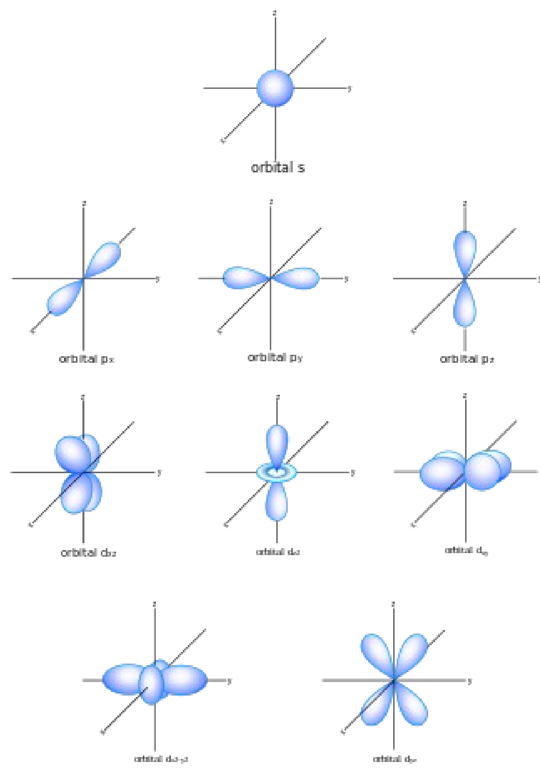
Early atomic physicists were mathematicians, which means that they came up with a really complicated mathematical model to describe the atom. Here's our new friend, the Schrödinger equation:

$$H(t)|\psi(t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle$$

This ought to clear things up.

There's a lot going on here, but what you need to know is that this equation and the model that's built around it is called the **quantum mechanical model of the atom**. This model of the atom has the following features:

- **It's got four quantum numbers instead of one**. You can think of these as the variables in the bigger, cooler equation that describes electrons.
- **Electrons still live in orbitals, but the orbitals are 3-D regions of space rather than 2-D circles**.[12] Here are some of them:



There are the simplest ones. Seriously.

12 *And, to make things complicated, the electrons are no longer little tiny points. Instead, they're 3-D waves that fill the 3-D orbitals. It's a complicated idea, and not even your teacher has any idea what this means. Frankly, nobody really understands what it means. It seems to work, though.*

- **The nucleus is still the same**. Protons, neutrons, in the middle of the atom, etc.

As for the rest of it, everything else is still valid. The whole idea behind spectra (i.e. jumping and falling from different orbitals) is still considered correct, except that the orbitals are now 3-D shapes rather than 2-D circles. Atoms are still really small and all the particles do the same stuff. Except in 3-D.

The Main Ideas in Chapter 3:

- **It's taken a long time to figure out what the deal with atoms is**. And we may have farther to go.
- **You should learn about Dalton's atomic theory, the Plum Pudding model, and Rutherford's model**. But I'm not going to rewrite them all just because you don't feel like going back a few pages.
- **The Bohr model of the atom is the one that teachers have been telling you about for years and years**. It's not right, but it does a nice job of explaining how atomic spectra occur.
- **The quantum mechanical model of the atom is the one we currently subscribe to**. It's pretty hard to understand, but so far, so good.

Images:

- **Cranky Democritus**: By Tomisti, Public Domain via Wikimedia Commons. Historical illustrations of Democritus either show him as a cranky guy or as being kind of ridiculous. From this, I think it's safe to say that Democritus was a heavy drinker.
- **Eyeball model**: See https://commons.wikimedia.org/wiki/File:Anatomical_model_of_an_eye,_Italy,_1601-1700_Wellcome_L0058732.jpg for author [CC BY 4.0 (http://creativecommons.org/licenses/by/4.0)], via Wikimedia Commons. There are actually pictures of Dalton's actual eyeballs, but I considered them to be too gross for this book. Which, considering some of the other pictures I've already shown you, should say something.
- **Plum pudding model**: By Tjlafave (Own work) [CC BY-SA 4.0 (http://creativecommons.org/licenses/by-sa/4.0)], via Wikimedia Commons. If you ask me, this looks a lot more like a "sphere of grape soda" mode of the atom.
- **Geiger-Marsden experiment**: By Kurzon (Own work) [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons. The Geiger in this experiment was the guy who came up with the Geiger counter, and Marsden worked extensively in New Zealand to advance science, particularly nuclear physics.
- **Silver**: By me (Image:Silver.gif) [CC BY-SA 2.5 (http://creativecommons.org/licenses/by-sa/2.5)], via Wikimedia Commons. And when it says "By me", that's the information that was given on the webpage. It wasn't actually me, as in Ian Guch, who came up with this picture. It was somebody who claims to be named "me." I just wanted to make that clear.
- **Lies**: By Name invalid (Own work) [Public domain], via Wikimedia Commons. I like graffiti images, so thought I'd include it. Don't come spray paint my house, though.
- **First Bohr atom**: By Halfdan, [CC BY-SA 3.0] via Wikimedia Commons.
- **Second Bohr atom**: By Jean-Jacques MILAN [Public domain], via Wikimedia Commons.
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- **Various atomic spectra**: By Herve-Darce (Own work) [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons. A great poster idea for the nerds in your life.
- **Bohr and Einstein**: [Public Domain], via Wikimedia Commons. These were apparently the two slouchiest guys in science.
- **Scary equation**: By YassineMrabet (Own work) [CC BY-SA 3.0] via Wikimedia Commons. To be precise, this is the time-dependent equation. The time-independent equation describes a standing wave. Which probably doesn't make sense, so don't worry about it too much.
- **Orbitals**: By Tim Kaluza (Own work) [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0) or GFDL (http://www.gnu.org/copyleft/fdl.html)], via Wikimedia Commons. In the real world, atoms can have nearly 60 filled orbitals, which is why nobody will show you all of them.