Lesson 8: Introduction to the Atom

Introduction

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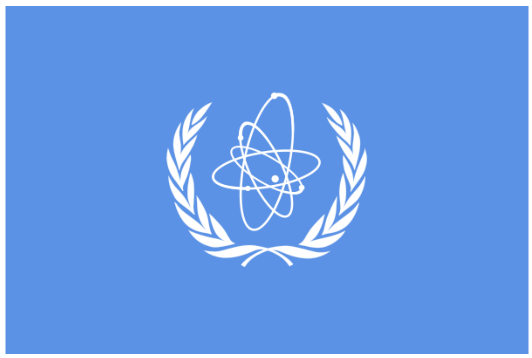
Lesson 8 – An Introduction to the Atom

You've heard the term "atom" before and doubtlessly have a pretty good idea of what it is. However, what you may *not* know is how we came to our current understanding of the atom. Not surprisingly, this required a great deal of insight, as well as a fair amount of trial and error.

What is an Atom?

The definition that's most relevant to chemists states that **atoms** are the smallest unit of matter that have the properties of an element. Everything that you would normally think of as a "thing" is made of atoms.[1] Your dog is made of atoms, as are disposable razors, air, and the Eiffel Tower.



The logo of the International Atomic Energy Agency, a department of the United Nations, shows a common, but incorrect, depiction of an atom.[2]

Though the definition above is a good first draft, it doesn't really explain what atoms are like. In order to understand how atoms work, we'll explore how people have thought about them through history.

Why explore the history of the atom?

You may wonder why anybody would feel the need to read about the history of the atom rather than just learning about our current understanding. The reason we do this is not just to force you to learn irrelevant information, but to help you to better understand the atom. As we'll see, atoms are not quite as easily understood as you may have been led to believe!

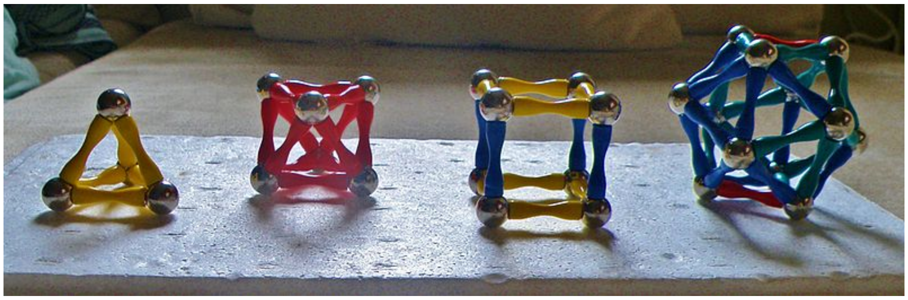
1 *See lesson 7 for a description of what we mean by "thing." Incidentally, this definition of the atom is based on the one on Wikipedia.*
2 *By IAEA (Flag code: [1]) [Public domain], via Wikimedia Commons.*

The Early Greek Model of the Atom

For most of man's history, we didn't have any idea what matter what made of. For that matter, we didn't really care, either. After all, you don't need to know what wood is in order to use it to build a home.

The first person to come up with a good understanding of the nature of matter was Leucippus (early 5th century BCE).[3] He believed that all matter was made up of indivisible atoms, and that the properties of matter could be attributed to the different ways that they were stacked together. This belief was referred to as **atomism**.

Plato (427 – 347 BCE) refined this idea somewhat. He believed that there were four elements (earth, air, fire, water) and that teach element was made of atoms that that were differently-shaped from each other. Thus, he believed that earth was made of cubic atoms, air was made of octahedral atoms, fire was made of tetrahedral atoms, and water was made of icosahedral atoms.



Right to left: Tetrahedron, octahedron, cube, icosahedron.

Aristotle (384 – 322 BCE) rejected the theory of the atom. He believed that objects weren't made of smaller atoms, but were instead continuous structures. Unlike atomists, who believed that things changed because the arrangements of atoms changed, Aristotle taught that things changed because they had a pre-existing ability to change from one thing to another, and that changes occurred because the matter simply actualized its earlier potential.

For approximately 2,000 years, Aristotle's view was the most widely-held. This may not make sense to us, but consider that the technology to test atomic views was still very far in the future. Because ancient philosophers believed in reason, it's not hard to understand why they would believe in a concept that made sense over one that couldn't be verified.

Discoveries of the Late 18th Century

For a long time, there was no way to test the various theories of the nature of matter. However, in the late 18th century, there were some interesting scientific discoveries that again got people thinking about atoms.

3 *The earliest atomic theory is frequently attributed to Democritus, one of Leucippus' students. Because none of Leucippus' works have survived, little is known about him.*

In 1789, Antoine Lavoisier devised the **law of conservation of mass**, which states that mass is neither created nor destroyed in any process. This seems obvious to us. After all, if you mix salt with water, you'd imagine the salt water would weigh the same as the weight of the salt plus the weight of the water. However, consider that, in many processes such as combustion reactions, some of the products are gases. If you burn a piece of wood, you may believe that, because the ash weighs less than the wood, the mass has changed over the reaction. For Lavoisier to determine otherwise was quite a discovery.

The next big discovery came in 1794, when Joseph Proust described the **law of definite proportions**[4], which states that chemical compounds consist of atoms combined in whole-number proportions. For example, water has the formula H_2O, never $H_{1.7}O$ or $H_{2.3}O$. Again, this may seem obvious to us with our modern technology, but it's only been relatively recently that we've been able to find the compositions of chemical compounds to a high degree of precision. A scientist of three hundred years ago may very well have found that the formula of water is $H_{1.7}O$ rather than H_2O, simply because of experimental error.

Joseph Proust, analytical chemist

Proust vs. Proust

For some reason, students tend to mix up the chemist Joseph Proust (1754 – 1826) with the writer Marcel Proust (1871 – 1922). Seriously, they're not the same guy.

Marcel Proust, author of À la recherche du temps perdu.

Dalton's Atomic Theory

In 1803, an English scientist named John Dalton assembled a lot of ideas that were going around the scientific community into a new model of the atom. In this theory, he stated that atoms have the following properties:

- Matter is made of tiny, indestructible atoms.
- All atoms of the same element have the same chemical and physical properties, different from those of other elements.
- Atoms of elements combine in whole-number ratios to form chemical compounds.[5]
- Atoms obey the law of conservation of mass.
- Chemical reactions occur when atoms are rearranged.

4 *Also called the "law of constant composition" or "Proust's Law."*
5 *Basically, the law of definite proportions, along with the law of multiple proportions, which we won't discuss because it doesn't really add much to the conversation.*

All of these laws probably seem reasonable to you, and it may seem as if they're all correct. Let's take a look at each of them and see if this is the case.

Matter is made of tiny indestructible atoms: Partially true

- Atoms are, indeed, very tiny. Hydrogen atoms are about 1.2×10^{-10} meters across, which means that you could stretch 630,000 of them across the length of a human hair. As to whether they're indestructible, the answer is "sort of." For us chemists, atoms are, for all intents and purposes, indestructible. However, when particle physicsts put enough energy into an atom, they can break it apart into much smaller pieces. A better statement would be to say that "atoms are tiny particles that are indestructible during chemical reactions."

All atoms of the same element have the same chemical and physical properties, apart from those of other elements. Partially true

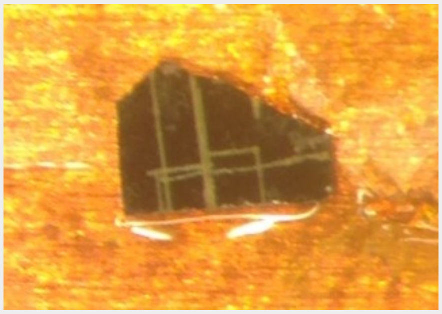
- Atoms of different elements do, in fact, have different chemical and physical properties. Though some properties may be similar to one another, no two elements have the same properties. However, when it comes to atoms of the same element, there can be small differences between isotopes of the element, which have different numbers of neutrons. We will talk about this in more detail in a later lesson.

Atoms of elements combine in whole-number ratios to form chemical compounds: Mostly true

- We understand that carbon dioxide has the formula CO_2, and don't expect anything like $CO_{2.1}$ to show up in a reaction. However, there is a class of materials called nonstoichiometric compounds, in which defects in their structure causes the ratios of elements to be something other than whole numbers. An important example of this are the palladium hydrides, which have the formula PdH_x, where x is somewhere between 0.02 and 0.58, depending on conditions.

Superconductors

Many superconductors are also nonstoichiometric compounds. The superconducting material YBCO ($YBa_2Cu_3O_{7-x}$) was the first "high temperature" material that retained its superconductive properties warmer than the temperature of liquid nitrogen (77 K, -196 °C). Superconductors are used in both medicine and science because they have no electrical resistance.[6]



6 *By SPat (Own work) [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons.*

Atoms obey the law of conservation of mass: True

- When you form a chemical compound, the mass of your products (i.e. what you make) will be equal to the mass of the reagents (i.e. what you started with). No problems here.[7]

Chemical reactions occur when atoms are rearranged: True

- All of chemistry is built around the fact that when you rearrange atoms, you get new chemical compounds that have different properties. This one is absolutely true!

For nearly a hundred years, Dalton's model of the atom was considered to be the final model of the atom. However, as we shall see shortly, things were to change.

<u>The main ideas in this lesson:</u>

- Atoms are the smallest units of matter that have the properties of elements.
- The law of conservation of mass states that matter is neither created nor destroyed during any process.
- The law of definite proportions states that compounds consist of atoms of elements combined in whole-number ratios.
- Dalton's model of the atom was the first really comprehensive one that described their properties and behavior.

7 *Read Lesson 7 for an explanation of why there are problems here.*

Lesson 8: Glossary

atom: The smallest unit of matter that has the properties of an element.

atomism: The belief that matter consists of small particles called atoms. The theory of atomism originated with ancient Greek philosophers.

law of conservation of mass: Matter can be neither created nor destroyed.

law of definite proportions: Chemical compounds are formed through the combination of atoms in whole number ratios.

superconductor: A material that conducts electricity without resistance.

Lesson 8: Practice Sheet

1) Though atomic theory was devised over two thousand years ago, it wasn't until relatively recently that was generally accepted by scientists. Given that we have definitively established the existence of atoms, why do you believe that it took so long for people to realize the truth?

2) Why is it generally OK for us to treat atoms as if they were indestructible particles?

3) Why do you think Plato and some other Greek philosophers believed that the atoms of each element had different shapes? Is this a reasonable belief for them to have had?

Lesson 8: Practice Sheet Answers

1) Though atomic theory was devised over two thousand years ago, it wasn't until relatively recently that was generally accepted by scientists. Given that we have definitively established the existence of atoms, why do you believe that it took so long for people to realize the truth?

Without evidence, philosophers and scientists had no way of knowing what matter was made of. The naked eye can't see objects smaller than around 0.1 mm. Given that atoms are a million times smaller than this, any guesses about the structure of atoms had to be just that: guesses. It wasn't until experimental evidence was gained through more careful measurements that people such as Dalton were able to infer the existence of atoms, and not until the 1970's when people were first able to see them at the Lawrence Berkeley Laboratories with an electron microscope.

2) Why is it generally OK for us to treat atoms as if they were indestructible particles?

For our purposes, they are indestructible particles. Though huge amounts of energy can be used to break atoms, these quantities of energy just aren't present when performing chemical reactions.

3) Why do you think Plato and some other Greek philosophers believed that the atoms of each element had different shapes? Is this a reasonable belief for them to have had?

Though the Greek philosophers were passionate about learning about the world, they had very little information from which to work. Given that they had given a great deal of thought to geometry, it makes sense that they believed the main distinguishing characteristic between the elements were their shapes. Though they could have just as easily picked another characteristic, their interests led them to believe that shape was the primary determination of atomic makeup.

<u>Lesson 8 Activity: Law of Conservation of Mass Lab</u>

Parent Information

Goal: To teach your child how the law of conservation of mass works

Home destruction factor: 2/10. There might be a little mess, but nothing too bad.

Safety: Though there are no major safety factors involved in doing this lab, it is probably best to have your child wear goggles.

Materials (do-it-yourself version): This will depend on what your child comes up with. However, a scale or balance will be required.

Materials (baking soda and vinegar version):
- 1 box of baking soda
- 1 bottle of 5% vinegar
- 1 scale or balance

Clean-up: This will vary depending on which version of the lab your child tries and what they've done. If baking soda and vinegar are used, the waste can be put down the sink.

How to perform this lab:

In this lab, your child will be asked to demonstrate the law of conservation of mass, which states that mass is neither created nor destroyed during any change. Depending on which version of this lab is used, this can be done in a couple of ways:
- Do-it-yourself version: Your child will simply be asked to "demonstrate the law of conservation of mass." How they do this will be up to them, with your approval.
- Baking soda and vinegar version: Your child will combine baking soda and vinegar, measuring and comparing the masses of the reagents and products.

The do-it-yourself version of this lab requires nothing in the way of preparation. When you tell your child to demonstrate the law of conservation of mass, they'll end up doing any one of a thousand different things to prove that mass remains constant during some process. Your child will have to get your approval before they can do this experiment, so you can make this lab as straightforward or as challenging as you'd like. Some good ways of demonstrating the law of conservation of mass:
- Bake something or otherwise prepare food items
- Mix baking soda and vinegar. This is the basis for the other version of this experiment, but it would not be surprising if your child came up with it on his/her own.
- Dissolving sugar or salt in water.
- Weighing two objects separately, then weighing them together. This may seem like a trivial example, but it does the job.

The baking soda and vinegar version of this lab requires that your child first weigh baking soda and vinegar, and then weigh the resulting solution formed when they are combined. Your child will come up with the experimental procedure on their own, but as this really consists only of combining baking soda and vinegar, this is a simple lab to run.

The surprise:

Unlike most other labs, this one has a surprise: It's nearly impossible to demonstrate the law of conservation of mass with the equipment we have at home. Sure, with trivial examples such as stacking books, we shouldn't have a problem. However, when you consider other examples, you can see where the problem starts:

- When you cook food, some of it splashes or evaporates out, resulting in a lower than expected mass.
- If dissolving things, you will frequently find that a small amount of either the thing being dissolved or the water splashes out, causing a lower than expected mass.

Most importantly for this lab, you'll find that when you combine baking soda and vinegar that the mass decreases significantly after the reaction occurs. This takes place because the bubbles of carbon dioxide given off have mass of their own, and this mass is equivalent to 30% of the mass of the reaction product! As a result, if you performed this reaction with pure acetic acid and pure sodium bicarbonate, 100 grams of reagent would turn into 70 grams of product.

In practice, the change will not be this drastic. We are not using pure acetic acid, so the actual percent change will be closer to 1.5%, as the water in the vinegar will not react. However, this change is unavoidable when performing this lab, regardless of any steps your child takes to avoid it.

The reason that this error is built into the lab is that we're trying to prove two main points:

- **Even simple ideas are hard to devise**: In this lab, we're essentially trying to prove something that's intuitively obvious to us. We know that the basic premise is true and that we can prove it. However, even with these advantages, we're unable to prove that the law of conservation of mass works! This makes it easier to understand that, while this idea is simple from a conceptual standpoint, it would have been much harder to learn from the historical perspective of the people doing the experiments.
- **Screwing up is normal**: You may think it's a little cruel to set up a lab where your child is unable to get the desired result. When you think about it, you've really set him or her up to fail. And failing is a terrible thing, right? Actually, it's not. When performing scientific experiments, failure is not just possible but *inevitable*. There's no such thing as a perfect experiment because the world is not a perfect place. By giving your child a lab in which you know they'll be unable to get a perfect answer, you'll be able to control the way in which they learn this lesson. Some kids are just fine with the idea that the world isn't a perfect place, while others will feel that anything less than perfection is abject failure. In this lab, you have the chance to be there when things go wrong and to tell them that *everything is just fine.*

Assessment:

Because there are many different ways to do this lab, there are several different criteria you should use in your assessment:

- **Did your child's conclusion support the law of conservation of mass?** Depending on how the experiment went, the answer could either be yes or no – both answers are fine, depending on the experimental results obtained by your child in the lab. However, if the answer is no, it should be clear from your child's lab that they understand that the law of conservation of mass is actually true and that its apparent invalidity is a function of normal experimental error.
- **Does your child understand why their experiment supports/doesn't support the law of conservation of mass?** It is sometimes the case that kids will say their conclusions are in line with the law of conservation of mass, simply because they know the law of conservation of mass is correct. Depending on the experimental data, your child should understand precisely *why* their data supports or refutes the law of conservation of mass.
- **Does your child understand the concept of experimental error?** Given that this lab is nearly impossible to do under any but the most trivial cases, it is important for your child to realize that experimental error is inevitable whenever performing an experiment. Furthermore, your child should understand that you will not expect perfection from him/her, so long as they show that they understand why the lab either did or did not work.
- **Does your child have any ideas about how their procedure can be improved?** Though experimental error is inevitable in the lab, it's also the case that there are always ways to minimize its impact. Your child should have at least two concrete ideas about how the lab can be better performed.

Do-It-Yourself Law of Conservation of Mass Lab

The goal of this lab is simple: Demonstrate the validity of the law of conservation of mass. You may do this using whatever equipment or supplies you believe are necessary, provided that the person supervising the experiment has given it his/her OK. For the lab write-up, please do the following:

1. Write a procedure explaining what you did.
2. Record whatever data you collected during the lab.
3. Analyze your data and determine whether it supported or disproved the law of conservation of mass.
4. If your experiment did not support the law of conservation of mass, explain why you believe this to be the case.
5. List two specific sources of experimental error that may have been present when you performed the lab.
6. Describe two specific improvements you could make to your lab to minimize the effect of experimental error.

Good luck!

Baking Soda and Vinegar Law of Conservation of Mass Lab

The goal of this lab is simple: Demonstrate the validity of the law of conservation of mass – this must be done through the combination of baking soda and vinegar. You may set up your experiment in whatever way you'd like, provided that the person supervising the experiment has given it his/her OK. For the lab write-up, please do the following:

1. Write a procedure explaining what you did.
2. Record whatever data you collected during the lab.
3. Analyze your data and determine whether it supported or disproved the law of conservation of mass.
4. If your experiment did not support the law of conservation of mass, explain why you believe this to be the case.
5. List two specific sources of experimental error that may have been present when you performed the lab.
6. Describe two specific improvements you could make to your lab to minimize the effect of experimental error.

Good luck!

Lesson 8 – Assessment

1) Explain how the Greek model of the atom differed from Dalton's model.

2) Dalton stated that all atoms of the same element have the same chemical and physical properties. Given that we now know that this isn't true, is this a reasonable assumption for him to have made? Explain why or why not.

3) It has been said that experimental error is inevitable. However, the author of this exam can state definitively that he has observed experimental results that showed no error whatsoever. How can we reconcile the idea that experimental error is inevitable with experiments observed to have no error?

Lesson 8 Assessment Answers

1) Explain how the Greek model of the atom differed from Dalton's model.

Dalton's laws are essentially the Greek model of the atom with some other stuff added to it. Dalton and early Greek philosophers agreed that atoms are very tiny particles that make up all of matter, and that the way in which they're combined determines what substance is present. However, Dalton had some additional ideas based on data unavailable to the Greeks:

- Atoms combine in whole-number ratios to form chemical compounds: The concept of chemical compounds wasn't really something the Greeks were familiar with, so they never came up with this.
- Atoms obey the law of conservation of mass: Lack of experimental data kept the ancient Greeks from even conceiving of this idea.

Ideas such as "atoms of the same element are all identical" and "atoms of different elements are all identical" are difficult to assess, based on the Greeks' limited understanding of how the world came together. Based on Plato's concept of the atom, however, it seems reasonable to assume that his model of the atom would support this.

For parents: This question is really asking two things: 1) Do you know how the Greek and Dalton models of the atom differ; and 2) Have you spent some time thinking about how they fit together? The specific answer your child gives doesn't necessarily have to be as in-depth as the one I gave above, so long as they've answered the two main parts of the question.

2) Dalton stated that all atoms of the same element have the same chemical and physical properties. Given that we now know that this isn't true, is this a reasonable assumption for him to have made? Explain why or why not.

It is entirely reasonable for him to have believed this. Not only was it difficult to perform precision experiments that would disprove this idea, but the very concept that the atom had internal structure that could vary was completely unknown.

3) It has been said that experimental error is inevitable. However, the author of this exam can state definitively that he has observed experimental results that showed no error whatsoever. How can we reconcile the idea that experimental error is inevitable with experiments observed to have no error?

A result of this is caused because of offsetting errors. Let's say, for example, that you attempt to verify the law of conservation of mass by weighing ice cream both before and after you transfer it from one place to another. You undoubtedly understand that this would cause errors, because some of the ice cream would be left behind in the original container. However, it may look as if the law of conservation of mass was verified if, for example, atmospheric moisture condensed on the ice cream in its new container. If the amount of mass lost by moving the ice cream was offset with an identical amount of condensation, it may look as if no ice cream was lost.

Lesson 8: References for Further Study

Everything you've ever wanted to know about Greek atomism:
https://plato.stanford.edu/entries/atomism-ancient/

About Aristotle's refutation of atomism: http://www.xenodochy.org/rekphd/chapter4.html

Lavoisier and the discovery of the law of conservation of mass:
http://www.uta.edu/faculty/sawasthi/Lecture%20Notes%20Chem1451/Law%20of%20Conservation%20of%20Mass.htm. Additionally, the last section is a very brief (but very good) discussion both of the apparent failings of the law of conservation of mass due to experimental error, as well as the law of conservation of mass-energy.

Defects and Nonstoichiometry: http://ww2.chemistry.gatech.edu/class/6182/wilkinson/nonstoi.pdf
This is a good, though technically-challenging, discussion of nonstoichiometric compounds (i.e. compounds that don't contain atoms in whole-number ratios).

Just How Small is an Atom? https://www.ted.com/talks/just_how_small_is_an_atom. An interesting YouTube video that covers a lot of ground regarding the sizes of atoms.