Lesson 10: Isotopes

Introduction

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Table of Contents:

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Lesson 10: Isotopes

Up to this point, we have discussed some of the historical models of the atom and how scientists came up with them. We're going to take a break from talking about atomic theory during this lesson and instead talk about some of the basics of atomic structure. Not to worry – we'll get to more advanced models of the atom in lesson 12.

The Parts of an Atom

As we've seen, atoms are made of three types of subatomic particle.[1] These particles are:

- **Protons** are positively-charged particles that lie in the nucleus of the atom. They have a mass of 1.00 atomic mass units (amu), which is equal to 1.67×10^{-27} kg.
- **Neutrons** are neutral particles in the nucleus. They have also have a mass of 1.00 amu.
- **Electrons** are negatively-charged particles that exist outside of the nucleus in places called "orbitals." Electrons have a mass of 0.00055 amu (which we usually just round to zero, as it's so small compared to the masses of protons and neutrons).

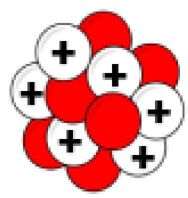


Diagram of an atomic nucleus. The protons have positive charge and the neutrons have no charge. The electrons (not shown) are outside of the nucleus. This is kind of complicated, and we'll talk about it in a future lesson.[2]

The Bohr and quantum models of the atom that we will learn about in Lesson 11 are mainly concerned with what electrons do out in atomic orbitals. In this lesson, we will discuss what goes on in the nucleus of atoms.

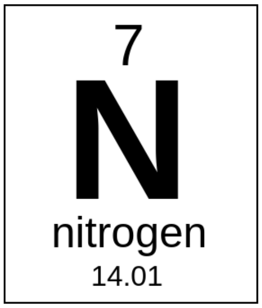
What makes an atom?

There are many different elements. You've heard of hydrogen, carbon, oxygen and probably many others. What is it that makes these elements different from one another?

The number of protons determines the type of element that an atom is. For example, atoms with three protons are one element (lithium), while atoms with four protons are another (beryllium). The number of protons that each element has is called its **atomic number**, and if you look on a periodic table it is found at the top of the box for that element. An example:

1 *Technically, there's a bit more to it than this, as protons and neutrons are themselves made up of smaller particles. However, these particles are not important in chemistry, so we won't be discussing them.*

2 *Figure based on atomic nucleus diagram by MikeRun (Own work) [CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0)], via Wikimedia Commons.*



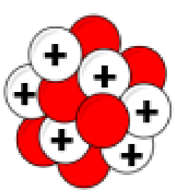
This is what the entry for nitrogen looks like on the periodic table. The "7" at the top center is its atomic number, and denotes that all nitrogen atoms have seven protons. We will discuss the "14.01" later.

Isotopes

You're probably aware that like charges repel one another and opposite charges attract. For example, the positive pole of a magnet will be repelled by the positive pole of another magnet and will be attracted by the negative pole of another magnet. In light of this, you may be wondering how all of the protons in an atomic nucleus can stick together in one place when they all have the same charge. After all, shouldn't they blow apart from each other? In a word, yes. Well, sort of.

It turns out that there are a couple of things that affect whether a nucleus will stay together. The first is something called the **strong nuclear force**, which is an attractive force between particles at very short distances, such as those found in an atomic nucleus. The strong nuclear force is named because, at these very tiny distances, it is by far the strongest of the elementary forces.

However, things start to get difficult if you pack a lot of protons into one place. Because protons all have positive charge, the repulsion between them will eventually cause the nucleus to blow apart as we had guessed earlier. Fortunately, neutrons are here to help. Neutrons, which have no charge, act as spacers that keep the protons from getting too close to one another and blowing apart. This doesn't keep the protons from repelling each other, but it does put enough space between them that the strong nuclear force can continue to hold the nucleus together.



Going back to our earlier picture of the nucleus, we can see that the neutrons (shown in red) help to space the protons apart from one another. This additional spacing keeps atomic nuclei stable. Without these neutrons, the protons would all be in contact with each other and would blow apart due to the mutual repulsion of positive charges.

In addition to just having spacers, atomic nuclei can have different numbers of spacers to keep the protons from coming into contact with one another. For example, there are two stable forms of nitrogen. Both forms contain seven protons, because that is nitrogen's atomic number. However, one form has seven neutrons, while the other has eight neutrons.

Isotopes, then, are the different forms of an element that result from having different numbers of neutrons. The **atomic mass** of an isotope is equal to the number of protons plus the number of neutrons in the isotope.

We can find the names of the isotopes and the numbers of protons and neutrons by doing some simple math. Let's take a look at the listing for iron on the periodic table:

26
Fe
iron
55.85

Based on the information here, how can we find the number of protons and neutrons for iron-56? You can do this by using the following guidelines:

- The atomic number is equal to the number of protons. This can be determined by the name of the element if you have a periodic table.
- The number of neutrons is equal to the atomic mass minus the number of protons. The atomic mass has to be given to you in the problem.
- The atomic mass of the isotope is equal to the number of protons plus the number of neutrons.

From this, we can determine the following:

- iron-56 has 26 protons. The listing on the periodic table tells us this.
- iron-56 has 30 neutrons. This is equal to the atomic mass (given to us as 56 in the problem) minus the atomic number (26).

Another way of asking a question involving this sort of information would be to say "what is the atomic mass of the isotope of iron with 29 neutrons? To solve this, you'd find the number of protons from the periodic table (26) and add 29 neutrons to get an atomic mass of 55. This isotope is referred to as "iron-55."

Referring to the isotopes of an element

In the question above, we referred to the isotope "iron-55", which refers to the isotope of iron that has a mass of 55 amu. There are two other ways that are commonly used to refer to this isotope. The first is ^{55}Fe *and the second is* $^{55}_{26}Fe$ *. The first term indicates only the atomic mass of this isotope and the atomic symbol, while the second also indicates the atomic number. Both terms have identical meaning, and mean the same thing as "iron-55."*

What about electrons?

The number of electrons is not something that we can figure out from this sort of calculation. Unlike both protons and neutrons, electrons can be easily removed from atoms, so we can't really say that an atom of iron-56 has to have any particular number of electrons. However, in *neutral* atoms of an element, the number of electrons will be equal to the number of protons. As a result, because iron-56 has 26 protons, we can say that a neutral atom of iron-56 also has 26 electrons.

How to solve sample problems:

The following are the sort of questions that are often asked about isotopes (answers are on the next page):

1) What element has 43 protons?

2) How many protons and neutrons does an atom of iodine-128 have?

3) What is the atomic mass of the isotope of selenium with 44 neutrons?

4) How many electrons are present in a neutral atom of chlorine-35?

The main ideas in this lesson:

- Protons are positively-charged particles in atomic nuclei with a mass of 1.00 amu.
- Neutrons are neutral particles in atomic nuclei with a mass of 1.00 amu. Neutrons are present in nuclei to separate the protons so they don't repel each other enough to blow the nucleus apart.
- Electrons are negatively-charged particles that exist outside of the nucleus in orbitals. They have a mass much smaller than that of protons and neutrons, and we usually just round the mass to zero.
- The atomic number of an element is the number of protons that it contains. All atoms of the same element have the same atomic number.
- Isotopes are the forms of an element that differ from one another by the number of neutrons present in the nucleus. This different number of neutrons results in different masses for each isotope.
- Atomic mass is the mass of an isotope of an element. It is equal to the number of protons plus the number of neutrons.
- The number of electrons in a neutral atom of an element is the same as the atomic number / number of protons.

Answers to the sample problems:

1) What element has 43 protons?
Looking at the periodic table, you can see that the element with an atomic number of 43 (i.e. the element with 43 protons) is technetium (Tc).

2) How many protons and neutrons does an atom of iodine-128 have?
The atomic number of iodine is 53, which means that all isotopes of iodine have 53 protons. To find the number of neutrons, subtract 53 from 128 to find that it has 75 neutrons.

3) What is the atomic mass of the isotope of selenium with 44 neutrons?
As we can see from the periodic table, selenium has 34 protons. The isotope with 44 neutrons has a mass of 34 + 44 = 78 amu.

4) How many electrons are present in a neutral atom of chlorine-35?
An atom of chlorine has 17 protons, so it must also have 17 electrons. This will be true for any isotope of chlorine, not just chlorine-35.

Lesson 10 Glossary:

atomic mass: The mass of an isotope, equal to the number of protons the element has plus the number of neutrons present in the isotope.

atomic number: The number of protons that all atoms of an element have. The atomic number is found on the periodic table above the atomic symbol of the element.

electrons: electrons are negatively-charged particles that reside outside of the nucleus in orbitals around the atom. They have such a low mass that, for most purposes, we just round down to zero.

isotopes: The different forms of an element that differ in how many neutrons they have and their atomic masses. The shorthand for an isotope is usually stated as "^{12}C" or "carbon-12", indicating the element and the atomic mass of that isotope.

neutrons: neutral particles that reside in the nuclei of atoms. They have a mass of 1.00 amu. The purpose of neutrons is to separate the protons in the nucleus so the mutual repulsion between protons doesn't cause them to blow the nucleus apart.

orbitals: The area outside the nucleus where electrons are found. We will discuss orbitals in much greater detail in future lessons.

protons: positively-charged particles that reside in the nuclei of atoms. They have a mass of 1.00 amu.

strong nuclear force: The force that causes the protons and neutrons in the nucleus to stick to one another.

Lesson 10 – Practice Sheet

1) Determine what symbols fit in the following chart using the information provided. The first row is given to you as an example:

isotope name	isotope symbol	# of protons	# of neutrons	# of electrons in a neutral atom	atomic mass of isotope
carbon-13	***^{13}C***	***6***	***7***	***6***	***13***
vanadium-51					
		44	67		
				38	89
	^{211}At				
		71			173

2) Why would it be unreasonable to expect that you could fill out the blanks in a table such as the one above if I only gave you the atomic mass of an isotope?

3) Explain why the number of protons and number of electrons must be the same for a neutral atom of an element.

4) Why do we treat the mass of an electron as essentially being zero?

Lesson 10 – Practice Sheet Answers

1) Determine what symbols fit in the following chart using the information provided. The first row is given to you as an example:

isotope name	isotope symbol	# of protons	# of neutrons	# of electrons in a neutral atom	atomic mass of isotope
carbon-13	***^{13}C***	***6***	***7***	***6***	***13***
vanadium-51	^{51}V	23	28	23	51
ruthenium-111	^{111}Ru	44	67	44	111
strontium-89	^{89}Sr	38	51	38	89
astatine-211	^{211}At	85	126	85	211
lutetium-173	^{173}Lu	71	102	71	173

How to solve this table:

- **The protons and atomic number are the same and are found on the periodic table.**
- **The number of electrons in a neutral atom are the same as the protons/atomic number.**
- **The atomic mass is equal to protons + neutrons**

2) Why would it be unreasonable to expect that you could fill out the blanks in a table such as the one above if I only gave you the atomic mass of an isotope?
Several different elements may have the same atomic mass. To fill out this chart, you need to know which element is present. For that, you need either an atomic symbol or number of protons in addition to the atomic mass.

3) Explain why the number of protons and number of electrons must be the same for a neutral atom of an element.
If an atom is neutral, this means that it has no overall positive or negative charge. Since protons and electrons have opposite charges, the numbers of each have to be the same to give an overall neutral charge.

4) Why do we treat the mass of an electron as essentially being zero?
The mass of electrons are so small compared to those of protons and neutrons that it's nearly insignificant when finding atomic mass.

Lesson 10 Lab Activity

In this lab, you will be examining a very common item: pennies. Though the pennies before you may look basically the same, you'll find that there are two distinct types of penny in this mixture. Think of them as being isotopes of the penny, so to speak.

Your job will be to determine what the two isotopes of pennies are. The differences between these isotopes has nothing to do with the condition of the penny, nor is it related to the changing pattern on the “tails” side of the penny over the years. It is a property of the penny itself that you have to determine.

You will be given a sack of pennies from which to make this determination. For your lab “write-up”, explain what you did to determine the different isotopes of pennies, show your data, and show how your data led to your conclusions.

Good luck!

Lesson 10 Lab Activity – Parent Notes

Objective: To creatively teach kids about the differences between different isotopes.

Equipment needed:

- A sack of pennies (around 100) that contains at least 20 pennies from before the year 1982. It is recommended that no pennies from 1982 be included.
- A balance/scale that has precision of at least 0.1 gram.

Safety: No safety issues

Room destruction factor: None

How the lab works:
Your child will be given a bunch of pennies from various years. By weighing the pennies from each year, he/she will find that the masses of the pennies break them into two different "isotopes":

- Pennies made before 1982 are made of 95% copper and 5% zinc, giving them a mass of 3.1 grams when new.[3]
- Pennies made after 1982 are made of 97.5% zinc and 2.5% copper, giving them a mass of 2.5 grams when new.
- Pennies made in 1982 may have either mass, as the formulation of the penny changed during this time. For this reason, it is recommended that no pennies from 1982 be included in this lab.

Potential issues with this lab:

- Pennies may be corroded or damaged. This should not cause a significant error in the mass of each penny, but if you measure to the nearest 0.01 gram you may notice it.
- Pennies have different markings on them. With the exception of 1943 steel pennies (which you are unlikely to get), this makes no difference at all in the mass of the pennies.
- Impatience with data collection. In order for this lab to work, your child will need to sit and weigh a hundred or so pennies, keeping track of each. This will be boring, but data collection is often methodical in this way.

Assessing the lab:
The lab states to your child that "For your lab 'write-up', explain what you did to determine the different isotopes of pennies, show your data, and show how your data led to your conclusions." This can be done in a number of different ways, and you should consider it to have been done correctly if the following are present:

- An explanation of your child's methodology
- The raw data (i.e. masses) from each penny, along with the corresponding year
- An explanation of how the raw data leads to their determination of the number of isotopes of pennies.

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3 *Pennies made between the years 1862-1962 have a mass of 3.1 grams as well, though the 5% that isn't copper contains tin. Pennies made in 1943 are made of zinc-plated steel and have a mass of 2.7 grams, but you are unlikely to find any.*

Lesson 10: Assessment

1) Determine what symbols fit in the following chart using the information provided. The first row is given to you as an example:

isotope name	isotope symbol	# of protons	# of neutrons	# of electrons in a neutral atom	atomic mass of isotope
	^{16}O				
		81	122		
lead-207					
		54			131
				41	92

2) Why would it be unreasonable for me to ask you how many protons, neutrons, and electrons were in an atom of fluorine?

3) What is the total positive charge in the nucleus of an osmium-190 atom?

4) If an osmium-190 atom has 74 electrons, what charge does this atom have as a whole?

5) Explain why the isotopes of an element have different numbers of neutrons.

Lesson 10: Assessment Answers

1) Determine what symbols fit in the following chart using the information provided. The first row is given to you as an example:

isotope name	isotope symbol	# of protons	# of neutrons	# of electrons in a neutral atom	atomic mass of isotope
oxygen-16	^{16}O	8	8	8	16
thallium-203	^{203}Tl	81	122	81	203
lead-207	^{207}Pb	82	125	82	207
xenon-131	^{131}Xe	54	77	54	131
niobium-92	^{92}Nb	41	51	41	92

2) Why would it be unreasonable for me to ask you how many protons, neutrons, and electrons were in an atom of fluorine?
Without knowing which isotope of fluorine we're talking about, it's impossible to guess the number of neutrons or the atomic mass. It is, however, possible to guess that the number of protons and electrons are both 9, as this is the case for every neutral atom of any isotope of fluorine.

3) What is the total positive charge in the nucleus of an osmium-190 atom?
76, as osmium has 76 protons in the nucleus.

4) If an osmium-190 atom has 74 electrons, what charge does this atom have as a whole?
+2, because there are two fewer negative electrons than positive protons.

5) Explain why the isotopes of an element have different numbers of neutrons.
Neutrons are required in atomic nuclei as spacers to keep protons from repelling each other enough to blow the nucleus apart. For each atom there are different numbers of neutrons that can each successfully stabilize the nucleus, giving rise to isotopes.

Lesson 10: Additional Resources

Subatomic particles:
Though we discussed protons, neutrons, and electrons in this lesson, it turns out that both protons and neutrons are composite particles that are made up of smaller subatomic particles. I recommend the Wikipedia article on subatomic particles if you're interested on learning more.

How compasses work:
Though this may not seem related, it turns out that compasses use the principles of “opposite charges attract, like charges repel” to help you figure out how to navigate on the open seas. https://adventure.howstuffworks.com/outdoor-activities/hiking/compass.htm

What effect do isotopes have in the real world?
The links below illustrate how different isotopes of the same element can cause differences in the chemical and physical properties of compounds:

- **Isotope effects in heavy water**: https://chemistry.stackexchange.com/questions/5084/chemical-properties-of-isotopes
- **How are the isotopes of elements separated from one another?** http://www.atomicheritage.org/history/isotope-separation-methods
- **Solving energy problems by mining helium-3 on the moon**: http://www.esa.int/Our_Activities/Preparing_for_the_Future/Space_for_Earth/Energy/Helium-3_mining_on_the_lunar_surface