Atomic Structure

To access a customizable version of this book, as well as other interactive content, visit www.ck12.org

CK-12 Foundation is a non-profit organization with a mission to reduce the cost of textbook materials for the K-12 market both in the U.S. and worldwide. Using an open-content, web-based collaborative model termed the **FlexBook®**, CK-12 intends to pioneer the generation and distribution of high-quality educational content that will serve both as core text as well as provide an adaptive environment for learning, powered through the **FlexBook Platform®**.

Printed: May 4, 2013

flexbook
next generation textbooks

CONCEPT 1 Atomic Structure

Lesson Objectives

The student will:

- identify the three major subatomic particles and their charges, masses, and location in the atom.
- briefly describe the discovery of the neutron.
- define atomic number.
- describe the size of the nucleus in relation to the size of the atom.
- explain what is meant by the atomic mass of an element and describe how atomic masses are related to carbon-12.
- define mass number.
- explain what isotopes are and how isotopes affect an element's atomic mass.
- determine the number of protons, neutrons, and electrons in an atom.
- calculate the atomic mass of an element from the masses and relative percentages of the isotopes of the element.

Vocabulary

- atomic mass
- atomic mass unit
- atomic number
- dalton
- isotopes
- mass number
- neutron
- strong nuclear force

Introduction

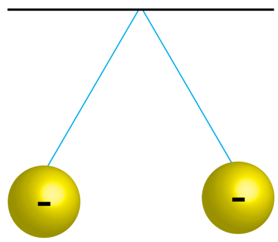
Dalton's atomic theory explained a lot about matter, chemicals, and chemical reactions. Nevertheless, it wasn't entirely accurate because, contrary to what Dalton believed, atoms can in fact be broken apart into smaller subunits or subatomic particles. The first type of subatomic particle to be found in an atom was the negatively charged electron. Since atoms are neutral, though, they must also contain positive material. In his gold foil experiment, Rutherford proved that the positive substance in an atom was concentrated in a small area at the center of the atom, leaving most the rest of the atom as empty space. In this lesson, we'll examine the subatomic particles making up the atom a little more closely.

This video gives basic information about the nucleus of atoms including comparative sizes of atom vs nucleus **(1e)**, see http://www.youtube.com/watch?v=Tfy0sIVfVOY (2:03).

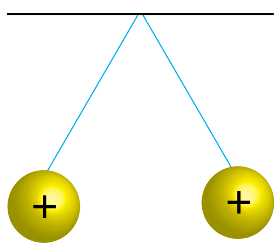
MEDIA
Click image to the left for more content.

Electrons, Protons, and Neutrons

Electrons have a negative charge. As a result, they are attracted to positive objects and repelled from negative objects, including other electrons (illustrated below). To minimize repulsion, each electron is capable of staking out a "territory" and "defending" itself from other electrons.

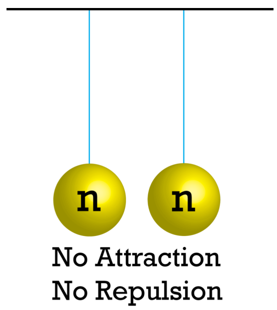


Protons are another type of subatomic particle found in atoms. They have a positive charge, so they are attracted to negative objects and repelled from positive objects. Again, this means that protons repel each other (illustrated below). However, unlike electrons, protons are forced to group together into one big clump, even though they repel each other. Protons are bound together by what are termed **strong nuclear forces**. These forces are responsible for binding the atomic nuclei together, allowing the protons to form a dense, positively charged center.

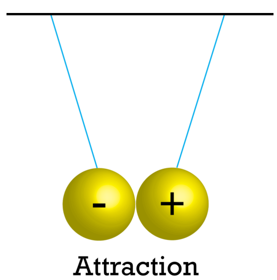


There is a third subatomic particle known as a **neutron**. Rutherford proposed the existence of a neutral particle along with the approximate mass of a proton, but it wasn't until years later that someone proved the existence of the neutron. A physicist named James Chadwick observed that when beryllium was bombarded with alpha particles, it emitted an unknown radiation that had approximately the same mass as a proton, but the radiation had no electrical charge. Chadwick was able to prove that these beryllium emissions contained a neutral particle – Rutherford's neutron.

As you might have already guessed from its name, the neutron is neutral. In other words, it has no charge and is therefore neither attracted to nor repelled from other objects. Neutrons are in every atom (with one exception), and they're bound together with other neutrons and protons in the atomic nucleus. Again, the binding forces that help to keep neutrons fastened into the nucleus are known as strong nuclear forces.



Since neutrons are neither attracted to nor repelled from objects, they don't really interact with protons or electrons beyond being bound into the nucleus with the protons. Protons and electrons, however, do interact. Using what you know about protons and electrons, what do you think will happen when an electron approaches a proton? Will the two subatomic particles be attracted to each other or repelled from each other? Here's a hint: "opposites attract, likes repel." Since electrons and protons have opposite charges (one negative, the other positive), you'd expect them to be attracted to each other, as illustrated below.



Even though electrons, protons, and neutrons are all types of subatomic particles, they are not all the same size. When comparing the masses of electrons, protons, and neutrons, you will find that electrons have an extremely small mass compared to the masses of either protons or neutrons (see **Figure** 1.1). On the other hand, the masses of protons and neutrons are fairly similar, with the mass of a neutron being slightly greater than the mass of a proton. Because protons and neutrons are so much more massive than electrons, almost all of the atomic mass in any atom comes from the nucleus, which is where all of the neutrons and protons are located.

FIGURE 1.1

Electrons are much smaller than protons or neutrons. How much smaller? If an electron was the size of a penny, a proton or a neutron would have the mass of a large bowling ball!

Table 1.1 gives the properties and locations of electrons, protons, and neutrons. The third column shows the masses of the three subatomic particles in grams. The second column, however, shows the masses of the three subatomic particles in amu, or atomic mass units. An **atomic mass unit (amu)** is defined as one-twelfth the mass of a carbon-12 atom (a carbon that has 6 protons and 6 neutrons). Atomic mass units are useful because, as you can see, the mass of a proton and the mass of a neutron are almost exactly 1.0 in this unit system. The **dalton** is equivalent to the atomic mass unit, with the two terms being different names for the same measure. The two terms are often used interchangeably, and both will be used throughout this text.

TABLE 1.1: Subatomic Particles, Properties, and Location

Particle	Relative Mass (amu)	Mass in Grams (g)	Electric Charge	Location
electron	$\frac{1}{1840}$	9.109383×10^{-28}	-1	outside nucleus
proton	1	$1.6726217 \times 10^{-24}$	$+1$	nucleus
neutron	1	$1.6749273 \times 10^{-24}$	0	nucleus

In addition to mass, another important property of subatomic particles is the charge. The fourth column in **Table** 1.1 shows the charges of the three subatomic particles. You already know that neutrons are neutral and thus have no charge at all. Therefore, we say that neutrons have a charge of zero. What about electrons and protons? Electrons are negatively charged and protons are positively charged, but the positive charge on a proton is exactly equal in magnitude (magnitude means "absolute value") to the negative charge on an electron. You may recall that Millikan discovered that the magnitude of the charge on a single electron is 1.6×10^{-19} C (coulomb), which means that the magnitude of the charge on a proton is also 1.6×10^{-19} C. In other words, a neutral atom must have exactly one electron for every proton. If a neutral atom has 1 proton, it must have 1 electron. If a neutral atom has 2 protons, it must have 2 electrons. If a neutral atom has 10 protons, it must have 10 electrons. Do you get the idea?

For a short animation demonstrating the properties of the electron using a cathode ray tube **(1h)**, see http://www.youtube.com/watch?v=4QAzu6fe8rE video (3:46).

MEDIA

Click image to the left for more content.

Atomic Number and Mass Number

Scientists can distinguish between different elements by counting the number of protons. If an atom has only one proton, we know it's an atom of the element hydrogen. An atom with two protons is always an atom of the element helium. When scientists count four protons in an atom, they know it's a beryllium atom. An atom with three protons is a lithium atom, an atom with five protons is a boron atom, an atom with six protons is a carbon atom... the list goes on (see **Figure** 1.2 for more examples).

Since an atom of one element can be distinguished from an atom of another element by the number of protons in the nucleus, scientists are always interested in this number and how this number differs between different elements. Therefore, scientists give this number a special name and a special symbol. An element's **atomic number (*Z*)** is equal to the number of protons in the nuclei of any of its atoms. The periodic table gives the atomic number of each element. The atomic number is a whole number usually written above the chemical symbol of each element in the table. The atomic number for hydrogen is $Z = 1$ because every hydrogen atom has 1 proton. The atomic number for helium is $Z = 2$ because every helium atom has 2 protons. What is the atomic number of carbon? (*Answer*: Carbon has 6 protons, so the atomic number for carbon is $Z = 6$.)

Since neutral atoms have to have one electron for every proton, an element's atomic number also tells you how many electrons are in a neutral atom of that element. For example, hydrogen has atomic number $Z = 1$. This means that an atom of hydrogen has one proton and, if it's neutral, one electron. Gold, on the other hand, has atomic number $Z = 79$, which means that a neutral atom of gold has 79 protons and 79 electrons.

The **mass number (*A*)** of an atom is the total number of protons and neutrons in its nucleus. Why do you think

FIGURE 1.2
How would you distinguish these three elements? You can't really distinguish between sulfur and gold based on color because both are yellowish. You could try to distinguish elements based on another parameter, such as shininess, but then how would you tell the difference between gold and silicon? Each element, however, does have a unique number of protons. Sulfur has 16 protons, silicon has 14 protons, and gold has 79 protons.

that the mass number includes protons and neutrons, but not electrons? You know that most of the mass of an atom is concentrated in its nucleus and that the mass of an electron is very, very small compared to the mass of either a proton or a neutron (like the mass of a penny compared to the mass of a bowling ball). By counting the number of protons and neutrons, scientists will have a very close approximation of the total mass of an atom.

mass number A = (number of protons) + (number of neutrons)

An atom's mass number is very easy to calculate once you know the number of protons and neutrons in the atom. Notice that the mass number is not the same as the mass of the atom. You can easily relate the mass number to the mass by recalling that both protons and neutrons have a relative mass of 1 amu.

Example:

What is the mass number of an atom that contains 3 protons and 4 neutrons?

(number of protons) = 3

(number of neutrons) = 4

mass number A = (number of protons) + (number of neutrons)

mass number $A = (3) + (4) = 7$

Example:

What is the mass number of an atom of helium that contains 2 neutrons?

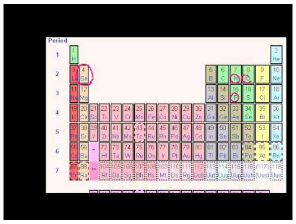
(number of protons) = 2 (Remember that an atom of helium always has 2 protons.)

(number of neutrons) = 2

mass number A = (number of protons) + (number of neutrons)

mass number $A = (2) + (2) = 4$

This video summarizes the concept of the atom and to the organization of the periodic table **(1a, 1e)**: http://www.youtube.com/watch?v=1xSQlwWGT8M (21:05).



MEDIA

Click image to the left for more content.

Isotopes and Atomic Mass

Unlike the number of protons, which is always the same for all atoms of the same element, the number of neutrons can be different. Atoms of the same element with different numbers of neutrons are known as **isotopes**. Since the isotopes of any given element all contain the same number of protons, they have the same atomic number. However, since the isotopes of a given element contain different numbers of neutrons, different isotopes have different mass numbers. The following two examples should help to clarify this point.

Example:

What is the atomic number (Z) and the mass number (A) of an isotope of lithium containing 3 neutrons? A lithium atom contains 3 protons in its nucleus.

atomic number Z = number of protons = 3

number of neutrons = 3

mass number A = (number of protons) + (number of neutrons)

mass number A = $(3) + (3) = 6$

Example:

What is the atomic number (Z) and the mass number (A) of an isotope of lithium containing 4 neutrons? A lithium atom contains 3 protons in its nucleus.

atomic number Z = number of protons = 3

number of neutrons = 4

mass number A = (number of protons) + (number of neutrons)

mass number A = $(3) + (4) = 7$

Notice that because the lithium atom always has 3 protons, the atomic number for lithium is always $Z = 3$. The mass number, however, is $A = 6$ for the isotope with 3 neutrons, and $A = 7$ for the isotope with 4 neutrons. In nature, only certain isotopes exist. For instance, lithium exists as an isotope with 3 neutrons and as an isotope with 4 neutrons, but it doesn't exists as an isotope with 2 neutrons or as an isotope with 5 neutrons.

This whole discussion of isotopes brings us back to Dalton's atomic theory. According to Dalton, atoms of a given element are identical. But if atoms of a given element can have different numbers of neutrons, then they can have different masses as well. How did Dalton miss this? It turns out that elements found in nature exist as uniform mixtures with a constant ratio of their naturally occurring isotopes. In other words, a piece of lithium always contains both types of naturally occurring lithium (the type with 3 neutrons and the type with 4 neutrons). Moreover, it always contains the two in the same relative amounts (or "relative abundances"). In a chunk of lithium, 93% will always be lithium with 4 neutrons, while the remaining 7% will always be lithium with 3 neutrons.

Unfortunately, Dalton always experimented with large chunks of an element – chunks that contained all of the naturally occurring isotopes of that element. As a result, when he performed his measurements, he was actually observing the averaged properties of all the different isotopes in the sample. Luckily, aside from having different masses, most other properties of different isotopes are similar.

Knowing about the different isotopes is important when it comes to calculating atomic mass. The **atomic mass** (sometimes referred to as atomic weight) of an element is the weighted average mass of the atoms in a naturally occurring sample of the element. Atomic mass is typically reported in atomic mass units. You can calculate the atomic mass of an element, provided you know the relative abundances the element's naturally occurring isotopes and the masses of those different isotopes. The examples below show how this calculation is done.

Example:

Boron has two naturally occurring isotopes. In a sample of boron, 20% of the atoms are B-10, which is an isotope of boron with 5 neutrons and a mass of 10 amu. The other 80% of the atoms are B-11, which is an isotope of boron with 6 neutrons and a mass of 11 amu. What is the atomic mass of boron?

Solution:

To do this problem, we will calculate 20% of the mass of B-10, which is how much the B-10 isotope contributes to the "average boron atom." We will also calculate 80% of the mass of B-11, which is how much the B-11 isotope contributes to the "average boron atom."

Step One: Convert the percentages given in the question into their decimal forms by dividing each percentage by 100%:

$$\text{Decimal form of } 20\% = 0.20$$

$$\text{Decimal form of } 80\% = 0.80$$

Step Two: Multiply the mass of each isotope by its relative abundance (percentage) in decimal form:

$$20\% \text{ of the mass of B-10} = 0.20 \times 10 \text{ amu} = 2.0 \text{ amu}$$

$$80\% \text{ of the mass of B-11} = 0.80 \times 11 \text{ amu} = 8.8 \text{ amu}$$

Step Three: Find the total mass of the "average atom" by adding together the contributions from the different isotopes:

$$\text{Total mass of average atom} = 2.0 \text{ amu} + 8.8 \text{ amu} = 10.8 \text{ amu}$$

The mass of an average boron atom, and thus boron's atomic mass, is 10.8 amu.

Example:

Neon has three naturally occurring isotopes. In a sample of neon, 90.48% of the atoms are Ne-20, which is an isotope of neon with 10 neutrons and a mass of 19.99 amu. Another 0.27% of the atoms are Ne-21, which is an isotope of neon with 11 neutrons and a mass of 20.99 amu. The final 9.25% of the atoms are Ne-22, which is an isotope of neon with 12 neutrons and a mass of 21.99 amu. What is the atomic mass of neon?

Solution:

To do this problem, we will calculate 90.48% of the mass of Ne-20, which is how much Ne-20 contributes to the "average neon atom." We will also calculate 0.27% of the mass of Ne-21 and 9.25% of the mass of Ne-22, which are how much the Ne-21 and the Ne-22 isotopes contribute to the "average neon atom" respectively.

Step One: Convert the percentages given in the question into their decimal forms by dividing each percentage by 100%:

$$\text{Decimal form of } 90.48\% = 0.9048$$

$$\text{Decimal form of } 0.27\% = 0.0027$$

$$\text{Decimal form of } 9.25\% = 0.0925$$

Step Two: Multiply the mass of each isotope by its relative abundance (percentage) in decimal form:

$$90.48\% \text{ of the mass of Ne-20} = 0.9048 \times 20.00 \text{ amu} = 18.10 \text{ amu}$$

$$0.27\% \text{ of the mass of Ne-21} = 0.0027 \times 21.00 \text{ amu} = 0.057 \text{ amu}$$

$$9.25\% \text{ of the mass of Ne-22} = 0.0885 \times 22.00 \text{ amu} = 2.04 \text{ amu}$$

Step Three: Find the total mass of the "average atom" by adding together the contributions from the different isotopes:

$$\text{Total mass of average atom} = 18.10 \text{ amu} + 0.057 \text{ amu} + 2.04 \text{ amu} = 20.20 \text{ amu}$$

The mass of an average neon atom, and thus neon's atomic mass, is 20.20 amu.

The periodic table gives the atomic mass of each element. The atomic mass is a number that usually appears below the element's symbol in each square. Notice that atomic mass of boron (symbol B) is 10.8 and the atomic mass of neon (symbol Ne) is 20.18, both which are very close to what we calculated in our examples. Take time to notice that not all periodic tables have the atomic number above the element's symbol and the atomic mass below it. If you are ever confused, remember that the atomic number should always be the smaller of the two and will be a whole number, while the atomic mass should always be the larger of the two. (The atomic mass must include both the number of protons and the average number of neutrons.)

Lesson Summary

- Electrons are a type of subatomic particle with a negative charge, so electrons repel each other but are attracted to protons.
- Protons are a type of subatomic particle with a positive charge, so protons repel each other but are attracted to electrons. Protons are bound together in an atom's nucleus as a result of strong nuclear forces.
- Neutrons are a type of subatomic particle with no charge (they're neutral). Like protons, neutrons are bound into the atom's nucleus as a result of strong nuclear forces.
- Protons and neutrons have approximately the same mass and are both much more massive than electrons (approximately 2,000 times as massive as an electron).
- The positive charge on a proton is equal in magnitude to the negative charge on an electron. As a result, a neutral atom must have an equal number of protons and electrons.
- Each element has a unique number of protons. An element's atomic number (Z) is equal to the number of protons in the nuclei of any of its atoms.
- The mass number (A) of an atom is the sum of the protons and neutrons in the atom
- Isotopes are atoms of the same element (same number of protons) that have different numbers of neutrons in their atomic nuclei.
- An element's atomic mass is the average mass of one atom of that element. An element's atomic mass can be calculated provided the relative abundances of the element's naturally occurring isotopes and the masses of those isotopes are known.
- The periodic table is a convenient way to summarize information about the different elements. In addition to the element's symbol, most periodic tables will also contain the element's atomic number and the element's atomic mass.

Further Reading / Supplemental Links

This website has a video called "Atomic Structure: The Nucleus" available.

- http://videos.howstuffworks.com/hsw/5806-atomic-structure-the-nucleus-video.htm

Review Questions

1. Decide whether each of the following statements is true or false.
    a. The nucleus of an atom contains all of the protons in the atom.
    b. The nucleus of an atom contains all of the neutrons in the atom.
    c. The nucleus of an atom contains all of the electrons in the atom.
    d. Neutral atoms of a given element must contain the same number of neutrons.
    e. Neutral atoms of a given element must contain the same number of electrons.
2. Match the subatomic property with its description in **Table** 1.2.

TABLE 1.2: Table for Problem 2

Subatomic Particle	Characteristics
i. electron	a. has an atomic charge of $+1\ e$
ii. neutron	b. has a mass of 9.109383×10^{-28} grams
iii. proton	c. is neither attracted to nor repelled from charged objects

3. Arrange the electron, proton, and neutron in order of decreasing mass.
4. Indicate which of the following statements is true or false.
    a. An element's atomic number is equal to the number of protons in the nuclei of any of its atoms.
    b. The symbol for an element's atomic number is A.
    c. A neutral atom with $Z = 4$ must have 4 electrons.
    d. A neutral atom with $A = 4$ must have 4 electrons.
    e. An atom with 7 protons and 7 neutrons will have $A = 14$.
    f. An atom with 7 protons and 7 neutrons will have $Z = 14$.
    g. A neutral atom with 7 electrons and 7 neutrons will have $A = 14$.
5. Use the periodic table to find the symbol for the element with:
    a. 44 electrons in a neutral atom.
    b. 30 protons.
    c. $Z = 36$.
    d. an atomic mass of 14.007 amu.
6. When will the mass number (A) of an atom be:
    a. bigger than the atomic number (Z) of the atom?
    b. smaller than the atomic number (Z) of the atom?
    c. equal to the atomic number (Z) of the atom?
7. In **Table** 1.3, Column 1 contains data for five different elements. Column 2 contains data for the same five elements but with different isotopes of those elements. Match the columns by connecting isotopes of the same element.

TABLE 1.3: Table for Problem 7

Column 1	Column 2
a. an atom with 2 protons and 1 neutron	i. a C (carbon) atom with 6 neutrons
b. a Be (beryllium) atom with 5 neutrons	ii. an atom with 2 protons and 2 neutrons
c. an atom with $Z = 6$ and $A = 13$	iii. an atom with $Z = 7$ and $A = 15$

TABLE 1.3: (continued)

Column 1	Column 2
d. an atom with 1 proton and $A = 1$	iv. an atom with $A = 2$ and 1 neutron
e. an atom with $Z = 7$ and 7 neutrons	v. an atom with $Z = 4$ and 6 neutrons

8. Match the following isotopes with their respective mass numbers in **Table** 1.4.

TABLE 1.4: Table for Problem 8

Column 1	Column 2
(a) an atom with $Z = 17$ and 18 neutrons	i. 35
(b) an H atom with no neutrons	ii. 4
(c) A He atom with 2 neutrons	iii. 1
(d) an atom with $Z = 11$ and 11 neutrons	iv. 23
(e) an atom with 11 neutrons and 12 protons	v. 22

9. Match the following isotopes with their respective atomic numbers in **Table** 1.5.

TABLE 1.5: Table for Problem 9

Column 1	Column 2
(a) a B (boron) atom with $A = 10$	i. 8
(b) an atom with $A = 10$ and 6 neutrons	ii. 2
(c) an atom with 3 protons and 3 neutrons	iii. 3
(d) an oxygen atom	iv. 4
(e) an atom with $A = 4$ and 2 neutrons	v. 5

10. Answer the following questions:
    a. What's the mass number of an atom that contains 13 protons and 13 neutrons?
    b. What's the mass number of an atom that contains 24 protons and 30 neutrons?
11. Answer the following questions:
    a. What's the mass number of the isotope of manganese (Mn) containing 28 neutrons?
    b. What's the mass number of the isotope of calcium (Ca) containing 20 neutrons?
12. Answer the following questions:
    a. What's the atomic number of an atom that has 30 neutrons, and a mass number of $A = 70$?
    b. What's the atomic number of an atom with 14 neutrons, if the mass number of the atom is $A = 28$?
13. Answer the following questions:
    a. What's the mass number of a neutral atom that contains 7 protons and 7 neutrons?
    b. What's the mass number of a neutral atom that contains 7 electrons and 7 neutrons?
    c. What's the mass number of a neutral atom that contains 5 protons, 5 electrons, and 6 neutrons?
    d. What's the mass number of a neutral atom that contains 3 electrons and 4 neutrons?
14. Answer the following questions:
    a. What element has 32 neutrons in an atom with mass number $A = 58$?
    b. What element has 10 neutrons in an atom with mass number $A = 19$?

15. Copper has two naturally occurring isotopes. 69.15% of copper atoms are Cu-63 and have a mass of 62.93 amu. The other 30.85% of copper atoms are Cu-65 and have a mass of 64.93 amu. What is the atomic mass of copper?

References

1. Image of the penny is from the United States Mint (http://en.wikipedia.org/wiki/Image:2005-Penny-Uncirculated-Obverse-cropped.png), image of bowling ball is by Scl chua (http://en.wikipedia.org/wiki/Image:Bowlingball.jpg). Composite image of bowling ball and penny. Both images are in the public domain
2. Sulfur image originally from the Smithsonian Institution (http://en.wikipedia.org/wiki/Image:Sulfur.jpg), gold image taken by Aram Dulyan (http://en.wikipedia.org/wiki/Image:Native_gold_nuggets.jpg), and silicon image created by Enricoros (http://en.wikipedia.org/wiki/Image:SiliconCroda.jpg). Composite of sulfur, gold, and silicon. All images are in the public domain