Activity 9

What Determines and Limits an Atom’s Mass?

GOALS
In this activity you will:
• Investigate the composition of the atom’s nucleus.
• Explain why the atomic masses of some elements are not whole numbers.
• Use symbols to represent different isotopes of an element.
• Determine the composition of the nucleus of an atom from its isotope symbol.
• Calculate the average atomic mass of an element from the percent abundance of its isotopes.

What Do You Think?
In Activity 4 you learned that the structure of an atom includes a nucleus surrounded by electrons. Most of the mass of an atom is concentrated in the small nucleus that has a positive electric charge equal in magnitude to the negative charge of all the electrons surrounding the nucleus.

• What do you think makes up the nucleus of the atom?

Record your ideas about this question in your Active Chemistry log. Be prepared to discuss your responses with your small group and the class.

Investigate
Part A: What’s in the Nucleus?
1. Atomic mass is the average mass of atoms of each element. Atomic number indicates the number of electrons in the atom and the number of protons located in the nucleus needed to produce an electrically neutral atom. Refer to the periodic table to answer the following questions:
a) How many protons are there in a hydrogen atom?

b) To the nearest whole number, what is the atomic mass of a hydrogen atom?

c) How many protons are there in a helium atom?

d) Since the mass of an electron is negligible, compared to the nucleus, what would you expect the atomic mass of a helium atom to be? Explain your answer.

e) To the nearest whole number, what is the atomic mass of a helium atom?

2. In Step 1, you found that the helium atom has a mass that is four times the mass of a hydrogen atom, while the electric charge on the helium nucleus is only twice that of the hydrogen atom. This suggests the presence of another particle in the nucleus, with about the same mass as the proton but no electric charge. This particle is called a neutron.

Sample:
Boron has atomic number 5. This informs you that there are 5 electrons and that the nucleus contains 5 protons. The average atomic mass of boron is 10.811 atomic mass units. Most boron has 11 atomic mass units and some has 10 atom mass units. Since the mass is the sum of the protons and the neutrons (electrons have very, very little mass) then you can conclude that most boron nuclides have 5 protons and 6 neutrons in the nucleus.

Refer to your table of atomic numbers and atomic masses to answer the following questions:

a) How many protons would you expect to find in the nucleus of a helium atom? (Recall that the number of protons needs to balance the number of electrons.)

b) How many neutrons would you expect to find? (The atomic mass is a combination of the mass of the protons and the mass of the neutrons.)

c) How many protons and neutrons would you expect to find in the nucleus of an atom of each of the following elements?

- lithium
- beryllium
- boron
- carbon
- nitrogen
- oxygen
- fluorine
- neon

3. Refer again to the periodic table.

a) What are the atomic masses of magnesium and chlorine? What are the atomic masses of sodium and fluorine? Which set is closer to whole numbers?

b) We expect protons and neutrons to exist in whole numbers. You cannot have part of a proton in the nucleus. What would you expect the atomic masses of most magnesium, chlorine, sodium, and fluorine atoms to be? Explain your answer.

4. The fact that some atomic masses are not close to whole number multiples of the atomic mass of hydrogen is now explained by the fact that the number of neutrons is not the same in all atoms of a given element. Only the number of protons, the atomic number, is the same in all atoms of a
given element. Atoms of the same element with different number of neutrons in the nucleus are known as isotopes (meaning “same number of protons”). Isotopes are identified by their mass number, the sum of the number of neutrons plus protons.

**Sample:**

Lithium has an atomic number of 3 and an average atomic mass of 6.941. All lithium atoms have 3 protons in the nucleus. A neutral atom of lithium always has 3 electrons to balance the charge of the three protons. The average atomic mass of a lithium atom is 6.941 atomic mass units, indicating that some lithium atoms have 3 neutrons, to make a total atomic mass of 6 and other lithium atoms have 4 neutrons, to make a total atomic mass of 7. These 2 isotopes are designated lithium-6 and lithium-7. Since there are so many more lithium-7 atoms, the average of all of the atoms is very close to 7.

Refer to your list of atomic masses to answer the following questions:

a) What isotopes (as indicated by their mass numbers) do you expect to account for the known atomic masses of the following elements?

- carbon (carbon-12 atoms with 6 neutrons and carbon-13 atoms with 7 neutrons; more carbon-12 atoms)

b) In the notation below, the mass number is written at the upper left of the chemical symbol of the element. The atomic number is written at the lower left of the chemical symbol of the element. How many neutrons and protons are present in the following isotopes?

<table>
<thead>
<tr>
<th>Isotopes</th>
<th>Neutrons</th>
<th>Protons</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{3}\text{He}$ and $^{4}\text{He}$</td>
<td>2, 3</td>
<td>1, 2</td>
</tr>
<tr>
<td>$^{6}\text{Li}$ and $^{7}\text{Li}$</td>
<td>3, 4</td>
<td>3, 3</td>
</tr>
<tr>
<td>$^{12}\text{C}$ and $^{13}\text{C}$</td>
<td>6, 7</td>
<td>6, 6</td>
</tr>
<tr>
<td>$^{14}\text{N}$ and $^{15}\text{N}$</td>
<td>7, 8</td>
<td>7, 7</td>
</tr>
</tbody>
</table>

**Part B: Forces within the Atom**

1. There are two very different forces acting on the electrons, protons, and neutrons in the atom. In order to better understand the atom, you must first understand these forces.

Cut two strips of transparent tape about 12 cm long. Bend one end of each strip under to form a tab. Place one strip sticky-side down on a table and label the tab “B,” for “bottom.” Place the other strip sticky-side down...
on top of the first strip and label the tab “T,” for “top.”

Peel off the top strip, using the tab, with one hand and then pick up the bottom strip with the other hand. Hold both strips apart, allowing them to hang down.

Slowly bring the hanging strips toward each other, but do not let them touch.

a) Record your observations.

b) If the strips accelerated toward or away from each other, Newton’s Second Law tells you that there must be a force. Is the force between the two strips of tape attractive or repulsive?

2. Make a second set of strips as in Step 1.

a) Predict what you think will happen if the two top strips are picked up, one from each set and brought toward each other. Record your prediction in your Active Chemistry log.

Pick up the two top strips by the tabs, allowing both strips to hang down. Slowly bring them toward each other.

b) Record your observations.

c) Was the force attractive or repulsive? Explain.

d) Predict what you think will happen if the two bottom strips of tape are picked up and brought toward each other. Record your prediction.

Pick up the two bottom strips by the tabs, allowing both strips to hang down. Slowly bring them toward each other.

e) Record your observations.

f) Was the force attractive or repulsive? Explain.

3. The two different strips of tape have different charges. The top strips have a positive electric charge. They have lost some of their electrons. Since the number of protons has remained the same, the strips are positive. The bottom strips have a negative charge. The bottom strips have gained some electrons. Since the number of protons has remained the same, the strips are negative. The force between the strips is called the electric force.

a) Is the force between two positive strips repulsive or attractive? Use evidence to justify your answer.

b) Is the force between two negative strips repulsive or attractive? Use evidence to justify your answer.

c) When a positive and a negative strip come near each other, is the force attractive or repulsive? Justify your answer.

4. The nucleus has a positive charge due to all of the protons there. The electrons surrounding the nucleus have negative charges.

a) What kind of electric force (attractive or repulsive) exists between the nucleus of an atom and any one of the atom’s electrons?

b) What kind of electric force (attraction or repulsion) exists between pairs of protons in the nucleus?
5. The nucleus is a very crowded place. The protons in the nucleus are very close to one another. If these protons are repelling each other by an electrostatic force (and they are!), there must be another force, an attractive force, that keeps them there. The attractive force is the nuclear force, also called the strong force. This force is much stronger than the electric force. It acts between pairs of protons, pairs of neutrons, and protons and neutrons. The electron is not affected by the nuclear force.

   a) Copy and complete the table below in your Active Chemistry log. The first row has been completed for you.

6. If the nucleus were too large, the protons on one side of the nucleus are too far away to attract the protons on the other side of the nucleus. The protons can still repel one another since the coulomb electrostatic force is long-range. The repulsive electrostatic force wins and the nucleus won’t form.

   A large nucleus will break apart when the electrostatic repulsion between the protons is too great.

The repulsion pushes the fragments of the nucleus apart, releasing a great amount of energy. This process of splitting an atom into smaller atoms is called fission. It occurs in uranium when an additional neutron is added and causes instability.

   One example of the fission process can be represented as follows:

   \[ ^{235}_{92}U + \_1n \rightarrow ^{94}_{36}Kr + ^{139}_{56}Ba + 3 \_1n + \text{energy} \]

   a) Is the mass number conserved on both sides of the reaction? What is the total mass number on each side?

   b) Is the atomic number conserved on both sides of the reaction? What is the total atomic number on each side?

   c) Why does the neutron have a mass number of 1?

   d) Why is the atomic number of a neutron equal to 0?

Small nuclei can also combine to form a larger nucleus and release energy. This process is called fusion.

<table>
<thead>
<tr>
<th>Particles</th>
<th>Coulomb electrostatic force</th>
<th>Strong, nuclear force</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron-proton</td>
<td>attractive</td>
<td>none</td>
</tr>
<tr>
<td>electron-neutron</td>
<td></td>
<td></td>
</tr>
<tr>
<td>proton-proton</td>
<td></td>
<td></td>
</tr>
<tr>
<td>proton-neutron</td>
<td></td>
<td></td>
</tr>
<tr>
<td>neutron-neutron</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
THENUCLEUSOFANATOM

DiscoveryoftheNeutron

Theaverageatomicmassesofsomeelementswereknownin
Mendeleev'stime,eventhoughscientistsdidn'tknowmuchaboutthe
actualstructureofanatom.InPartAofthisactivityyouexplored
theideaofhowtheatomicmassrelatestotheatomicnumber.
Mendeleevbeganorganizinghisperiodictablebylistingalltheknown
elementsinordertoatomicmass.However,hefoundthatorganizing
theelementsinthiswaydidnotalwaysmakem sensewithintermsofthe
behavioroftheelements.Heconcludedthathismeasurements
ofatomicmasswereincorrectandinthesesituationsusedthe
propertiesoftheelementstoplacetheminthetable.

Asitturnedout,Mendeleev'smeasurements werenecessarily
flawed.Although early models of thenucleus included the proton, the
proton alone could not account for the fact that the mass of a helium
atom is four times the mass of a hydrogen atom while the electric
chargeontheheliumnucleusisto twice that of thehydrogenatom.
Lord Rutherford (afterdiscoveringthatatomshadanucleus)
addressedthisproblemwhenshesuggestedthatanotherparticlewas
presentinthenucleus,withaboutthesamemassastheprotonbut
noelectriccharge.Henamedthisparticle theneutron.

The neutron was actually discovered in 1932 (by Chadwick,aBritish
physicist), adding agreatdealtounderstandingofthenucleusof
theatom.Thisclescoverydidnotsolveallofthemysteriesconcerning
theatomicmassesofsomeelements.Scientiststodayrefertoprotons
and neutrons as nucleons since they reside in thenucleusand are
almostidenticalinmass.Themassnumbertellsusthenumber
ofnucleons.

Isotopes

InPartAofthisactivityyoualsoinvestigatedwhytheatomicmassof
anelementisnotawholenumber.Notallatomsofgivenelement
havethesame-numberofneutronsinthenucleus.Onlythenumber
ofprotons, the atomic number, is the same in all atomsofagiven
element. Atoms of the same element with different number of
neutrons in the nucleus are known as **isotopes** (meaning “same number of protons”). Isotopes are identified by their mass number, the sum of the number of neutrons plus protons.

You can refer to an element by its name (chlorine), by its atomic symbol (Cl), or by its atomic number (17). All three identifications are equivalent and used interchangeably in chemistry. The same element can have a different number of neutrons in the nucleus. Chlorine, which must have 17 protons in the nucleus, can have 18 or 20 neutrons. Chlorine with 20 neutrons and chlorine with 18 neutrons are the isotopes of chlorine ($^{35}\text{Cl}$ and $^{37}\text{Cl}$).

**Electrostatic and Nuclear Forces**

In **Part B** of this activity, when you brought the two positive strips near each other, they experienced a repulsive force. This was true for two negative strips as well. When a positive and a negative strip were brought close together, the force was attractive. As you have heard, “opposites attract!”

Inside the nucleus, the protons are repelling one another. Every pair of protons has a repulsive force between them. The force is very large because the distances within the nucleus are very small. The nucleus is between 10,000 and 100,000 times smaller than the atom. The electrical force can be described mathematically.

\[
F = \frac{kq_1q_2}{d^2}
\]

where $F$ is the force,

$k$ is Coulomb’s constant (a number $= 9 \times 10^9$ N m$^2$/C$^2$),

$q_1$ and $q_2$ are the charges, and

$d$ is the distance between the charges.

As the distance between the charges increases the force weakens. Since the distance in the denominator is squared, if the distance triples the electrical force is 9 times ($3^2$) weaker or one-ninth as strong.
The question then becomes, what holds the protons together in the nucleus? The protons do have an electrical force pushing them apart but they have the larger nuclear force holding them together. The nuclear force is strong at short range. Anywhere beyond a distance of approximately $10^{-14}$ m (that’s less than one 10-millionth of one 10-millionth of a meter), the nuclear force is zero. Neutrons in the nucleus are also attracted to each other and to protons with the nuclear force. Electrons are not affected by the nuclear force. Electrons belong to a different class of particles than protons and neutrons and do not interact with the strong nuclear force.

The nucleus is held together by a new force—the strong nuclear force. The nuclear force:

- is very, very strong at small distances;
- acts only between nucleons (proton-proton, proton-neutron, neutron-neutron);
- is always attractive;
- is very short range (if nucleons are more than $10^{-14}$ m apart, the nuclear force is zero).

The atom is held together by the electrostatic coulomb force. The electrostatic force:

- is strong at small distances, weak at large distances;
- acts only between charged particles (proton-proton, electron-electron, proton-electron);
- is attractive or repulsive;
- is long range (the force gets weaker at large distances).

All the nucleons are attracted by the nuclear force. The electrostatic force repelling protons in the nucleus is overwhelmed by the attractive nuclear force between these protons.

**Unstable Atoms**

You might expect to find nuclei of atoms with all sorts of combinations of neutrons and protons. Yet the quantity of isotopes for each element is rather small, and the number of elements is also limited. Moreover, elements do not occur in nature with atomic number greater than 92, and the highest atomic number for an atom created in the laboratory is 117.
There are two stable masses of chlorine, chlorine-35 and chlorine-37. The key word in this statement is “stable.” There are other isotopes of chlorine, both heavier and lighter than chlorine-35 and chlorine-37, but they are not stable. The unstable isotopes can convert to a more stable combination of neutrons and protons, and they do so according to a systematic pattern in time. These other isotopes of chlorine are said to be radioactive. Understanding why certain elements are radioactive requires a deeper understanding of the structure of the nucleus. Scientists are still trying to fully understand stability of the elements.

If the nucleus of an atom is too large, the protons on one side of the nucleus are too far away to attract the protons on the other side of the nucleus. The protons can still repel one another since the coulomb electrostatic force is long-range. The interaction between the repulsive electrostatic force and the attractive nuclear force is one determining factor on the maximum size of a nucleus.

The stability of an atom varies with the elements. Light elements become more stable as the atomic mass (the number of nucleons) increases. The most stable element is iron (atomic number 26) with an atomic mass of 56. Elements with larger atomic masses become less stable.

In general, elements with nuclear mass much, much less than 56 can combine to gain mass, become more stable, and give off energy. This process is called fusion. Elements with nuclear mass much, much greater than 56 can break apart to lose mass, become more stable, and give off energy. This process is called fission.

Fusion is the process of small nuclei combining to increase their mass. The best example of fusion processes is what occurs in the Sun and other stars. The fusion process is ideal for supplying safe energy because it releases very large amounts of energy without leaving much dangerous radioactive residue. However, it is very difficult to accomplish this on an industrial level at the present time. In the future we hope scientists will figure out how to harness the energy of nuclear fusion, because it would be an excellent source of energy for society.

The process of splitting an atom into smaller atoms is called fission. This is the process that is used to produce nuclear energy. It is used to power nuclear submarines and to produce electrical energy in nuclear power plants all over the world.
The use of nuclear energy for the production of electricity is quite apparent as you look at the numerous states that depend on nuclear energy. For example, over 40% of Illinois’ electricity is produced by nuclear energy. Nuclear fission does create some major problems: (1) Security, (2) Radiation, (3) Removal of spent rods, and (4) Disposal of waste. With these problems, there is a need for continued research. Numerous universities and government facilities are trying to improve the efficiency of nuclear fission and at the same time, trying to develop nuclear fusion for commercial use. This ongoing research is expensive and depends on the government, industry, and other organizations to continue supporting this research. If we can learn how to harness nuclear fusion we can alleviate our nation’s electrical problems while decreasing pollution. The field of nuclear science is going to continue to grow and the future will provide great opportunities for a young scientist like you to get involved.

Checking Up

1. Explain the difference between atomic mass and atomic number.
2. What two forces are at work in the nucleus of an atom? Explain how each works.
3. What is an isotope?
4. Why are some isotopes unstable?
5. Construct a table or diagram to compare and contrast the nuclear processes of fission and fusion.
Reflecting on the Activity and the Challenge

In Part A of this activity you learned that the mass of an atom, concentrated in the nucleus, is due to two types of particles, the proton and the neutron. Elements are identified by their atomic number, the number of protons in the nucleus. The atomic mass, the average mass of an atom of a given element, listed on the periodic table is a reflection of the variety of isotopes of a given element that exist. How will you incorporate your expanded understanding of the contents of an atom’s nucleus, average atomic masses and isotopes into your game about the periodic table?

In Part B of this activity you also learned that only some combinations of neutrons and protons in a nucleus are stable, depending on the balance between the strong force holding the nuclear particles together and the electric force pushing them apart. The nuclear force is a short-range force. Beyond a distance of approximately $10^{-14}$ m, the nuclear force has no strength. Within that distance, this force between protons and protons, protons and neutrons, and neutrons and neutrons is quite strong. Recognizing the interplay between the electric force in the nucleus and the strong, attractive nuclear force provides an insight into the size of nuclei and the maximum size of a nucleus. These insights can be incorporated into your periodic table game in a creative way.

Chemistry to Go

1. If lithium loses an electron to become Li+, what is the average atomic mass of the lithium ion? Explain how you arrived at your answer.

2. Hydrogen has 3 isotopes with mass numbers of 1, 2, and 3. Write the complete chemical symbol for each isotope.

3. Give the complete chemical symbol for the element that contains 16 protons, 16 electrons, and 17 neutrons.

4. Complete the table below: (Use the periodic table.)

<table>
<thead>
<tr>
<th>Chemical symbol</th>
<th>$^{39}_{19}$K</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic number</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of protons</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of electrons</td>
<td>53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of neutrons</td>
<td>10</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Atomic mass</td>
<td>127</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5. Neutrons can be used to bombard the nucleus of an atom like uranium. Why would it be more difficult to inject the nucleus of uranium with a proton?
6. Complete the following reaction: \( \frac{235}{92} \text{U} + \frac{1}{0} \text{n} \rightarrow \frac{94}{38} \text{Sr} + \_ \_ \_ + 2 \frac{1}{0} \text{n} \)

7. Radon is a threat to the well-being of people in their homes because it emits radioactive particles at a significant rate. Complete the following radioactive decay equation:
\( \frac{222}{86} \text{Rn} \rightarrow \frac{218}{84} \text{Po} + \_ \_ \_ \)

8. Explain why a helium atom is able to exist. What keeps the 2 electrons, 2 protons, and 2 neutrons together?

**Inquiring Further**

Calculating average atomic mass

If you know the percentages of abundance for the isotopes of a chemical element and the known masses of those isotopes, you can calculate the average atomic mass of that element. The process is similar to calculating the average age of students in your class — add up each person’s age and divide by the number of students in your class. However, if you had to average the age of all of the students in your high school, you might choose another route. It would be easier to find out how many students are fourteen, how many are fifteen, and so on. Then you could multiply the number of students in each age group by that age. Then you would add these subsets together and divide by the total number of students.

A similar process is used to average the masses of different isotopes of an element. Consider the element chlorine. There are two stable isotopes of chlorine, chlorine-35 and chlorine-37. Of all the chlorine atoms on Earth, 75.77% of them are the isotope chlorine-35, each having a mass of 34.96885. The other 24.23% of stable chlorine atoms are the isotope chlorine-37, each having a mass of 36.96590. This means that 75.77 out of 100 chlorine atoms have a mass of 34.96885 and 24.23 have a mass of 36.96590. To find the average mass, the number of each isotope is multiplied by that isotope’s mass. Then the products are added together. The sum is divided by 100, since the information pertained to 100 chlorine atoms. The result is an average atomic mass of 35.45 for chlorine, the same value stated in the periodic table. The math is shown below:

Chlorine-35 \( 34.96885 \times 75.77 = 2649.6 \)

Chlorine-37 \( 36.96590 \times 24.23 = 895.7 \)

\( 3545.3 ÷ 100 = 35.453 \)

Magnesium, another isotope you investigated, has three stable isotopes as follows:

<table>
<thead>
<tr>
<th>mass number</th>
<th>isotopic mass</th>
<th>% abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>23.98504</td>
<td>78.99</td>
</tr>
<tr>
<td>25</td>
<td>24.98594</td>
<td>10.00</td>
</tr>
<tr>
<td>26</td>
<td>25.98259</td>
<td>11.01</td>
</tr>
</tbody>
</table>

Calculate the average atomic mass for magnesium. Describe how you arrived at your answer. You may use the process described above or challenge yourself to develop your own process.