Chapter 3
The Structure of Matter and the Chemical Elements

An Introduction to Chemistry
By Mark Bishop
Chemistry

The science that deals with the structure and behavior of matter
• A *model* is a simplified approximation of reality.

• Scientific models are simplified but *useful* representations of something real.
• All matter is composed of tiny particles.
• The particles are in constant motion.
• Increased temperature reflects increased motion of particles.
• Solids, liquids and gases differ in the freedom of motion of their particles and in how strongly the particles attract each other.
Solid

- Constant shape and volume
- The particles are constantly moving, colliding with other particles, and changing their direction and velocity.
- Each particle is trapped in a small cage whose walls are formed by other particles that are strongly attracted to each other.
The Nature of Solids

1. Friction of moving parts causes temperature to rise.
2. As temperature rises, particles move faster and bump harder.
3. Neighboring particles are pushed farther apart, and the solid expands.
4. If the lubricating or cooling system fails, engine expansion may cause a piston to jam in the cylinder.

Moving particles bump and tug one another but stay in the same small space.
Liquid

- Constant volume but variable shape
- The particles are moving fast enough to break the attractions between particles that form the walls of the cage that surround particles in the solid form.
- Thus each particle in a liquid is constantly moving from one part of the liquid to another.
Particles move fast enough for attractions to be constantly broken and reformed.

Particles are less organized, with slightly more space between them than in the solid.

Particles move throughout the container.
Evaporation

This particle is getting a sharp triple kick.

The kick propels the particle out of liquid.

It is traveling too fast for the attractions to the liquid particles to draw it back, so it is now a gas particle.
- Variable shape and volume
- Large average distances between particles
- Little attraction between particles
- Constant collisions between particles, leading to constant changes in direction and velocity
The Nature of Gases

Because particles are so far apart, there is usually no significant attraction between them.

Particles move in straight paths, changing direction and speed when they collide.
Description of Solid

- Particles constantly moving.
- About 70% of volume occupied by particles…30% empty.
- Strong attractions keep particles trapped in cage.
- Constant collisions that lead to changes in direction and velocity.
- Constant volume and shape due to strong attractions and little freedom of motion.
Particles constantly moving.
• About 70% of volume occupied by particles...30% empty
• Attractions are strong but not strong enough to keep particles from moving throughout the liquid.
• Constant collisions that lead to changes in direction and velocity.
• Constant volume, due to significant attractions between the particles that keeps the particles at a constant average distance, but not constant shape, due to the freedom of motion.
Description of Gas

- Particles constantly moving in straight-line paths
- About 0.1% of volume occupied by particles...99.9% empty.
- Average distance between particles is about 10 times their diameter.
- No significant attractions or repulsions.
- Constant collisions that lead to changes in direction and velocity.
- Variable volume and shape, due to lack of attractions and a great freedom of motion.

https://preparatorychemistry.com/KMT_Canvas.html
Separation of Salt Water

Salt water

Distillation

Salt

Electric current

Sodium metal

Chlorine gas

These substances are elements, because they cannot be broken down into simpler substances by chemical means.

Water

Electric current

Hydrogen gas

Oxygen gas
Distillation

1. Salt water is placed in this flask and heated.

2. Water evaporates and water vapor travels through here.

3. Salt does not evaporate, so it remains here.

4. Water is collected here.
118 Known Elements

• 83 are stable and found in nature.
  – Many of these are very rare.
• 7 are found in nature but are radioactive.
• 28 are not natural on the earth.
  – 2 or 3 of these might be found in stars.
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The periodic table is color-coded to highlight different groups and periods.
Metals, Nonmetals, and Metalloids
Characteristics of Metallic Elements

- Metals have a shiny metallic luster.
- Metals conduct heat well and conduct electric currents in the solid form.
- Metals are malleable.
  - For example, gold, Au, can be hammered into very thin sheets without breaking.
Classification of Elements

Main-group or representative elements

Transition metals

Inner transition metals
Solid, Liquid, and Gaseous Elements
• Tiny...about $10^{-10}$ m
  – If the atoms in your body were 1 in. in diameter, you’d bump your head on the moon.

• Huge number of atoms in even a small sample of an element
  – 1/2 carat diamond has $5 \times 10^{21}$ atoms...if lined up, would stretch to the sun.
Particles in the Atom

- **Neutron (n)**
  - 0 charge
  - 1.00867 u
  - in nucleus

- **Proton (p)**
  - +1 charge
  - 1.00728 u
  - in nucleus

- **Electron (e⁻)**
  - -1 charge
  - 0.000549 u
  - outside nucleus
What do we know about charge?

- Only some particles have it.
- There are two types of charge, plus and minus.
- It’s the characteristic of matter that leads to electromagnetic forces due to passing photons back and forth.
- Like charges repel.
- Opposite charges attract.
- The closer the charges, the stronger the force.
- The higher the charges, the stronger the force.
“If I seem unusually clear to you, you must have misunderstood what I said.”

Alan Greenspan,
Head of the Federal Reserve Board

“It is probably as meaningless to discuss how much room an electron takes up as to discuss how much room a fear, an anxiety, or an uncertainty takes up.”

Sir James Hopwood Jeans,
English mathematician, physicist and astronomer (1877-1946)
Electron Cloud for Hydrogen Atom

The negative charge is most intense at the nucleus and diminishes in intensity with increased distance from the nucleus.

http://preparatorychemistry.com/Hydrogen_1.html
Helium Atom

https://preparatorychemistry.com/helium_atom_Canvas.html
Carbon Atom

Carbon atom
6 protons
6 neutrons
(in most carbon atoms)
6 electrons
(in uncharged atom)

<table>
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<tr>
<th>Particle</th>
<th>Charge</th>
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<tr>
<td>proton</td>
<td>+1</td>
<td>1.00728 u (1.6726 × 10^{-24} g)</td>
</tr>
<tr>
<td>neutron</td>
<td>0</td>
<td>1.00867 u (1.6750 × 10^{-24} g)</td>
</tr>
<tr>
<td>e(^{-})</td>
<td>-1</td>
<td>0.000549 u (9.1096 × 10^{-28} g)</td>
</tr>
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Cloud representing the -6 charge from six electrons
• *Ions* are charged particles due to a loss or gain of electrons.

• When particles lose one or more electrons, leaving them with a positive overall charge, they become *cations*.

• When particles gain one or more electrons, leaving them with a negative overall charge, they become *anions*. 
Example
Ions

**Uncharged sodium atom, Na**
11 protons
11 electrons

**Cloud representing the -11 charge from 11 electrons**

**Loss of 1 electron**

**+11 charge in the nucleus**

**+1 sodium ion, Na⁺**
11 protons
10 electrons

**+8 charge in the nucleus**

**-8 charge from 8 electrons**

**Gain of 2 electrons**

**Uncharged oxygen atom, O**
8 protons
8 electrons

**-2 oxygen ion, O²⁻**
8 protons
10 electrons
• **Isotopes** are atoms with the same atomic number but different mass numbers.

• **Isotopes** are atoms with the same number of protons and electrons in the uncharged atom but different numbers of neutrons.

• **Isotopes** are atoms of the same element with different masses.
Isotopes of Hydrogen

All hydrogen atoms have 1 electron and 1 proton.

Different isotopes have different numbers of neutrons.

Negative charge cloud for the 1 electron of each hydrogen atom

https://preparatorychemistry.com/Hydrogen_1__Canvas.html
https://preparatorychemistry.com/Hydrogen_2__Canvas.html
https://preparatorychemistry.com/Hydrogen_3__Canvas.html
Possible Discovery of Elements 113 and 115

- Dubna, Russia
- Dubna’s Joint Institute for Nuclear Research and Lawrence Livermore National Laboratory
- Bombarded a target enriched in americium, $^{243}\text{Am}$, with calcium atoms, $^{48}\text{Ca}$.
- From analysis of decay products, they concluded that four atoms of element 115 were created.
Elements
113 and 115

• Created $^{288}115$, which lasted about 100 milliseconds...a very long time for this large an isotope.
• $^{288}115$ emitted an $\alpha$-particle, $^4\text{He}$, to form $^{284}113$.
• The results need to be confirmed.
Why try to make elements that last such a short time?

• To support theories of the nature of matter.
  – The standard model of the nature of matter predicts that elements with roughly 184 neutrons and 114 protons would be fairly stable. (See next slide.)
  – $^{288}$115, which lasted a relatively long time, has 115 protons and 173 neutrons.
Band of Stability

The image shows a graph that illustrates the band of stability in nuclear physics. The x-axis represents the number of protons, while the y-axis represents the number of neutrons. The graph highlights the relationship between these two quantities and the stability of the resulting nuclei. The yellow band indicates the region of stability, with the red line showing the one-to-one neutron to proton ratio. The highlighted area, labeled as the 'Island of Stability,' represents a specific region within this band where nuclei are particularly stable.
The technology developed to make new elements is also being used for medical purposes.

- Heavy-ion therapy as a treatment for inoperable cancers
  - Beams of carbon atoms shot at tumor.
  - Heavier particle beam is less likely to scatter.
  - Releases most of energy at end of path so easier to focus.
Effect on Chemical Changes

- **Electrons**
  - Can be gained, lost, or shared...actively participate in chemical changes
  - Affect other atoms through their -1 charge

- **Protons**
  - Affect other atoms through their +1 charge
  - Determine the number of electrons in uncharged atoms

- **Neutrons**
  - No charge...no effect outside the atom and no direct effect on the number of electrons.
Tin has ten natural isotopes.
To Describe Structure of Elements

- What particles?
  - Noble gases – atoms
  - Other nonmetals - molecules
    - Diatomic elements – H₂, N₂, O₂, F₂, Cl₂, Br₂, I₂
    - S₈, Se₈, P₄
    - C(diamond) huge molecules
  - Metallic elements – cations in a sea of electrons
• **Solid, liquid, or gas?**
  – Gases - $\text{H}_2$, $\text{N}_2$, $\text{O}_2$, $\text{F}_2$, $\text{Cl}_2$, $\text{He}$, $\text{Ne}$, $\text{Ar}$, $\text{Kr}$, and $\text{Xe}$
  – Liquids – $\text{Br}_2$ and Hg
  – Solids – the rest

• **Standard description of (1) solid, (2) liquid, (3) gas, or (4) metal.**
Helium Gas, He

2 protons and 2 neutrons in a tiny nucleus

-2 charge cloud from 2 electrons
Hydrogen, $\text{H}_2$, Molecule

Hydrogen nuclei

The two electrons generate a charge cloud surrounding both nuclei.

Space-filling model
Emphasizes individual atoms

Ball-and-stick model
Emphasizes bond
Hydrogen Gas, $\text{H}_2$

Each particle is a diatomic molecule.
Bromine Liquid, $\text{Br}_2$

Each particle is a diatomic molecule.
Iodine
Solid

https://preparatorychemistry.com/element_properties_Canvas.html
Typical Metallic Solid and Its “Sea of Electrons”

Atoms are packed closely together.

Cations lie in planes.

Electrons move freely, forming a sea of negative charge.

Sea-of-Electrons Model
Making Phosphoric Acid

- Furnace Process for making $\text{H}_3\text{PO}_4$ to be used to make fertilizers, detergents, and pharmaceuticals.
  - React phosphate rock with sand and coke at 2000 °C.
    $$2\text{Ca}_3(\text{PO}_4)_2 + 6\text{SiO}_2 + 10\text{C} \rightarrow 4\text{P} + 10\text{CO} + 6\text{CaSiO}_3$$
  - React phosphorus with oxygen to get tetraphosphorus decoxide.
    $$4\text{P} + 5\text{O}_2 \rightarrow \text{P}_4\text{O}_{10}$$
  - React tetraphosphorus decoxide with water to make phosphoric acid.
    $$\text{P}_4\text{O}_{10} + 6\text{H}_2\text{O} \rightarrow 4\text{H}_3\text{PO}_4$$
Sample Calculations (1)

- What is the maximum mass of $\text{P}_4\text{O}_{10}$ that can be formed from $1.09 \times 10^4$ kg P?
- The formula for $\text{P}_4\text{O}_{10}$ provides us with a conversion factor that converts from units of P to units of $\text{P}_4\text{O}_{10}$.

\[
1 \text{ molecule } \text{P}_4\text{O}_{10} \quad \frac{1}{4} \text{ atoms P}
\]
• What is the minimum mass of water that must be added to $2.50 \times 10^4$ kg $P_4O_{10}$ to form phosphoric acid in the following reaction?

$$P_4O_{10} + 6H_2O \rightarrow 4H_3PO_4$$

• The coefficients in the balanced equation provide us with a conversion factor that converts from units of $P_4O_{10}$ to units of $H_2O$.

$$\frac{6 \text{ molecules } H_2O}{1 \text{ molecule } P_4O_{10}}$$
Goal: To develop conversion factors that will convert between a measurable property (mass) and number of particles.
Counting by Weighing for Nails

• **Step 1:** Choose an easily measurable property.
  – Mass for nails

• **Step 2:** Choose a convenient unit for measurement.
  – Pounds for nails
• **Step 3:** If the measurable property is mass, determine the mass of the individual objects being measured.
  
  – Weigh 100 nails: 82 are 3.80 g, 14 are 3.70 g, and 4 are 3.60 g

• **Step 4:** If the objects do not all have the same mass, determine the weighted average mass of the objects.
  
  \[
  0.82(3.80 \text{ g}) + 0.14(3.70 \text{ g}) + 0.04(3.60 \text{ g}) = 3.78 \text{ g}
  \]
Counting by Weighing for Nails (cont)

- **Step 5:** Use the conversion factor from the weighted average to make conversions between mass and number of objects.

\[
? \text{nails} = 218 \text{ lb} \text{ nails} \times \left( \frac{453.6 \text{ g}}{1 \text{ lb}} \right) \left( \frac{1 \text{ nail}}{3.78 \text{ g}} \right) = 2.62 \times 10^4 \text{ nails}
\]
• **Step 6:** Describe the number of objects in terms of a collective unit such as a dozen, a gross, or a ream.

\[
\frac{? \text{ g nails}}{1 \text{ gross nails}} = \left( \frac{3.78 \text{ g nails}}{1 \text{ nail}} \right) \left( \frac{144 \text{ nails}}{1 \text{ gross nails}} \right) = \frac{544 \text{ g nails}}{1 \text{ gross nails}}
\]

\[
? \text{ gross nails} = 218 \text{ lb nails} \left( \frac{453.6 \text{ g}}{1 \text{ lb}} \right) \left( \frac{1 \text{ gross nails}}{544 \text{ g nails}} \right) = 182 \text{ gross nails}
\]
Counting by Weighing for Carbon Atoms

• **Step 1**: Choose an easily measurable property.
  – Mass for carbon atoms

• **Step 2**: Choose a convenient unit for measurement.
  – Atomic mass units (u) for carbon atoms
  – Atomic mass unit (u) = $1/12$ the mass of a carbon-12 atom (with 6 p, 6 n, and 6 e−)
• **Step 3:** If the measurable property is mass, determine the mass of the individual objects being measured.
  – For carbon: 98.90% are 12 u and 1.10% are 13.003355 u

• **Step 4:** If the objects do not all have the same mass, determine the weighted average mass of the objects.

\[
0.9890(12 \text{ u}) + 0.0110(13.003355 \text{ u}) = 12.011 \text{ u}
\]
• **Step 5:** Describe the number of objects in terms of a collective unit such as a dozen, a gross, or a ream, and use this and the weighted average to create a conversion factor to make conversions between mass and number of objects.
A **mole** (mol) is an amount of substance that contains the same number of particles as there are atoms in 12 g of carbon-12.

To four significant figures, there are $6.022 \times 10^{23}$ atoms in 12 g of carbon-12.

Thus a mole of natural carbon is the amount of carbon that contains $6.022 \times 10^{23}$ carbon atoms.

The number $6.022 \times 10^{23}$ is often called **Avogadro’s number**.
Avogadro’s Number

If the extremely tiny atoms in just 12 grams of carbon are arranged in the line, the line would extend over 500 times the distance between Earth and the sun.
Molar Mass Development

From the definition of an unified atomic mass unit, u

\[
\frac{12 \text{ g C-12}}{1 \text{ atom C-12}}
\]

From the definition of mole

\[
\frac{12 \text{ g C-12}}{1 \text{ mol C-12}}
\]

Weighted average masses of atoms of elements

\[
\begin{align*}
\frac{12.011 \text{ u C}}{1 \text{ atom C}} & \quad \frac{24.3050 \text{ u Mg}}{1 \text{ atom Mg}} & \quad \frac{15.9994 \text{ u O}}{1 \text{ atom O}} & \quad \frac{1.00794 \text{ u H}}{1 \text{ atom H}}
\end{align*}
\]

From relative atomic masses

\[
\begin{align*}
\frac{12.011 \text{ g C}}{1 \text{ mol C}} & \quad \frac{24.3050 \text{ g Mg}}{1 \text{ mol Mg}} & \quad \frac{15.9994 \text{ g O}}{1 \text{ mol O}} & \quad \frac{1.00794 \text{ g H}}{1 \text{ mol H}}
\end{align*}
\]
Molar Mass For Elements

- Atomic Mass from the Periodic Table

\[
\frac{(\text{atomic mass}) \text{ g element}}{1 \text{ mol element}}
\]

\[
? \text{ mol C} = 0.55 \text{ carat C} \left( \frac{1 \text{ g}}{5 \text{ carat}} \right) \left( \frac{1 \text{ mol C}}{12.011 \text{ g C}} \right) = 9.2 \times 10^{-3} \text{ mol C}
\]

or \(5.5 \times 10^{21} \text{ C atoms}\)