Chapter 2
The Structure of Matter and the Chemical Elements

An Introduction to Chemistry
By Mark Bishop
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.
Kinetic Molecular Theory

- 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.
• 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.
Liquids

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.

Surface of liquid

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.
Gas

- 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
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.
Separation of Salt Water

Salt water

Distillation

Salt

Electric current

Sodium metal

Chlorine gas

Hydrogen gas

Oxygen gas

Water

Electric current

These substances are elements, because they cannot be broken down into simpler substances by chemical means.
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.
Group Numbers on the Periodic Table

<table>
<thead>
<tr>
<th>Group</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1H</td>
<td>2H</td>
<td>3H</td>
<td>4H</td>
<td>5H</td>
<td>6H</td>
<td>7H</td>
<td>8H</td>
<td>9H</td>
<td>10H</td>
<td>11H</td>
<td>12H</td>
</tr>
<tr>
<td>2</td>
<td>3Li</td>
<td>4Be</td>
<td>5Na</td>
<td>6Mg</td>
<td>7Al</td>
<td>8Si</td>
<td>9P</td>
<td>10S</td>
<td>11Cl</td>
<td>12Ar</td>
<td>13K</td>
<td>14Ca</td>
</tr>
<tr>
<td>3</td>
<td>19K</td>
<td>20Ca</td>
<td>41Sr</td>
<td>38Sr</td>
<td>39Y</td>
<td>40Zr</td>
<td>41Nb</td>
<td>42Mo</td>
<td>43Tc</td>
<td>44Ru</td>
<td>45Rh</td>
<td>46Pd</td>
</tr>
<tr>
<td>4</td>
<td>37Rb</td>
<td>38Sr</td>
<td>71Lu</td>
<td>72Hf</td>
<td>73Ta</td>
<td>74W</td>
<td>75Re</td>
<td>76Os</td>
<td>77Ir</td>
<td>78Pt</td>
<td>79Au</td>
<td>80Hg</td>
</tr>
<tr>
<td>5</td>
<td>55Cs</td>
<td>56Ba</td>
<td>103Lr</td>
<td>104Rf</td>
<td>105Db</td>
<td>106Sg</td>
<td>107Bh</td>
<td>108Hs</td>
<td>109Mt</td>
<td>110Ds</td>
<td>111Rg</td>
<td>112Uub</td>
</tr>
<tr>
<td>6</td>
<td>57La</td>
<td>58Ce</td>
<td>59Pr</td>
<td>60Nd</td>
<td>61Pm</td>
<td>62Sm</td>
<td>63Eu</td>
<td>64Gd</td>
<td>65Tb</td>
<td>66Dy</td>
<td>67Ho</td>
<td>68Er</td>
</tr>
<tr>
<td>7</td>
<td>89Ac</td>
<td>90Th</td>
<td>91Pa</td>
<td>92U</td>
<td>93Np</td>
<td>94Pu</td>
<td>95Am</td>
<td>96Cm</td>
<td>97Bk</td>
<td>98Cf</td>
<td>99Es</td>
<td>100Fm</td>
</tr>
<tr>
<td>Group Names</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Alkali Metals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Alkaline Earth Metals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Halogens</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Noble Gases</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Period</th>
<th>Group</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1A</td>
<td>H</td>
</tr>
<tr>
<td>2</td>
<td>2A</td>
<td>He</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>Li, Be</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>Na, Mg</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>K, Ca</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Kr</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>Y, Zr, Nb, Mo, Tc, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, Xe</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>Lu, Hf, Ta, W, Re, Os, Ir, Pt, Au, Hg, Tl, Pb, Bi, Po, At, Rn</td>
</tr>
<tr>
<td>6</td>
<td>9</td>
<td>Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>Dy, Ho, Er, Tm, Yb</td>
</tr>
</tbody>
</table>

**Notes:**
- Elements are listed in order of their increasing atomic number.
- Periods correspond to the number of electron shells.
- Groups indicate the number of outermost electrons.
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

#### Periods

<table>
<thead>
<tr>
<th>2</th>
<th>Li</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>K</td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Cs, Ba</td>
</tr>
<tr>
<td>7</td>
<td>Ra</td>
</tr>
</tbody>
</table>

#### Solids

<table>
<thead>
<tr>
<th>6</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

#### Liquids

#### Gases

<table>
<thead>
<tr>
<th>1</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>N, O, F, Ne</td>
</tr>
<tr>
<td>3</td>
<td>Cl, Ar</td>
</tr>
<tr>
<td>4</td>
<td>Br, Kr</td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Hg, Rn</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>6</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

La, Yb
Ac, No
• 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
“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
Carbon atom

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

<table>
<thead>
<tr>
<th>Particle</th>
<th>Charge</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<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>
</tbody>
</table>

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

Uncharged oxygen atom, O
8 protons
8 electrons

Loss of 1 electron
+11 charge in the nucleus
Cloud representing the −11 charge from 11 electrons

+11 charge in the nucleus
−10 charge from 10 electrons

Gain of 2 electrons
+8 charge in the nucleus
−8 charge from 8 electrons

+8 charge in the nucleus

−2 oxygen ion, O^{2−}
8 protons
10 electrons

+1 sodium ion, Na^{+}
11 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.

Nucleus: 1 proton

Nucleus: 1 proton 1 neutron

Nucleus: 1 proton 2 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.
• Created $^{288}_{115}$, which lasted about 100 milliseconds...a very long time for this large an isotope.
• $^{288}_{115}$ emitted an $\alpha$-particle, $^4$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 graph illustrates the relationship between the number of neutrons and the number of protons, showing the band of stability and the island of stability. The one-to-one neutron to proton ratio is also highlighted.
Why try to make elements that last such a short time? (cont.)

- 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
To Describe Structure of Elements (2)

• Solid, liquid, or gas?
  – Gases - H₂, N₂, O₂, F₂, Cl₂, He, Ne, Ar, Kr, and Xe
  – Liquids – Br₂ 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

2 He
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, $H_2$

Each particle is a diatomic molecule.
Bromine Liquid, 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