Early Atomic Theory

Atoms, Molecules, and Ions

Preparation of College Chemistry
Luis Avila
Columbia University
Department of Chemistry
Atoms

<table>
<thead>
<tr>
<th>Atomic theory</th>
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<table>
<thead>
<tr>
<th>Components of the Atom</th>
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<table>
<thead>
<tr>
<th>Atomic Number</th>
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<table>
<thead>
<tr>
<th>Mass Number</th>
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<table>
<thead>
<tr>
<th>Isotopes</th>
</tr>
</thead>
</table>
 Atomic Theory. Early Thoughts

EMPEDOCLES: 470 BC
• Matter is composed of four elements: EARTH, AIR, WATER, FIRE

LEUCIPUS of Miletus and his disciple DEMOCRITUS of Abdera: 440 BC
• Nature consists solely of an infinite number of indivisible particles, having shape, size, impenetrability, and no further properties. These particles move through an otherwise empty space.
• The shape, size, location, and movement of these particles make up literally all of the qualities, relations, and other features of the natural world.

PLATO and ARISTOTLE reinforces: 384 - 270 BC
• Matter is composed of four elements: EARTH, AIR, WATER, FIRE
GALILEO GALILEI:

- Appearance of a new substance through chemical change involves rearrangement of parts too small to be seen.

FRANCIS BACON:

- Heat might be a form of motion of small particles.

ROBERT BOYLE and ISAAC NEWTON:

- Used atomic concepts to interpret physical phenomena.
Dalton’s Model of the Atom

1. Elements consist of tiny particles called atoms.

2. Atoms of the same element are alike in mass and size.

3. Atoms combine to form compounds in simple numerical ratios, such as 1:2, 2:3, etc.

4. Atoms of two elements may combine in different ratios to form more than one compound.
Consequences of Dalton’s Law

The Law of conservation of Mass:

“There is no detectable change in mass in an ordinary chemical rxn.”

The Law of Constant Composition:

“A compound always contains the same elements in the same proportions by mass.”

The Law of Multiple Proportions:

“The masses of one element that combine with a fixed mass of the second element are in a ratio of small whole numbers.”
**Composition of Compounds**

A compound always contains two or more elements combined in a definite proportion by mass.

Atoms of two or more elements may combine in different ratios to produce more than one compound.

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Hydrogen Peroxide</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Percent H</strong></td>
<td>11.2</td>
<td>5.9</td>
</tr>
<tr>
<td><strong>Percent O</strong></td>
<td>88.8</td>
<td>94.1</td>
</tr>
<tr>
<td><strong>Atomic Composition</strong></td>
<td>$2H + O$</td>
<td>$2H + 2O$</td>
</tr>
</tbody>
</table>
Certain substances \textit{when dissolved in water} can conduct an electric current.

\begin{itemize}
\item \textbf{MICHAEL FARADAY:} \hspace{1cm} \text{1830’s}
\item \textit{Water is not necessary} IONIC SUBSTANCES conduct electricity \textit{when melted}.
\item \textbf{SVANTE ARRHENIUS:} \hspace{1cm} \text{1887}
\item CATIONS: \textit{POSITIVE IONS}, that “travel” to the CATHODE (negative electrode)
\item ANIONS: \textit{NEGATIVE IONS} that “travel" to the ANODE (positive electrode).
\end{itemize}

\begin{itemize}
\item \textbf{G. J. STONEY:} \hspace{1cm} \text{1891}
\item There must be some FUNDAMENTAL unit of electricity associated with atoms: \textit{The ELECTRON}.
\end{itemize}
Cathode rays are ELECTRONS ($e^-$) particles with a negative charge.
Cathode ray tube

- Cathode
- Zinc sulfide screen
- Anode
- Electrons
- Magnet
The Nuclear Atom

"It was as though you had fired a fifteen-inch shell at a piece of tissue paper and it had bounced back and hit you."

ERNEST RUTHERFORD and HANS GEIGER with the apparatus for counting alpha particles
Manchester, 1912
Rutherford's scattering experiment

- Transmitted beam containing most of the alpha particles with only small deflection
- A few alpha particles are scattered at large angles
- Gold foil
- Source of narrow beam of fast moving \( \alpha \) particles
- Zinc sulfide screen
The Nuclear Atom
Arrangement of Subatomic Particles

Nucleus

Electron region
Atomic Number, Z

Equals number of protons in nucleus

Equals number of electrons in neutral atom

Location of the element in the Periodic Chart

Characteristic of a particular element
# Properties of Subatomic Particles

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass (kg)</th>
<th>Relative Mass (amu)</th>
<th>Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>proton</td>
<td>$1.67262 \times 10^{-27}$</td>
<td>1</td>
<td>+1</td>
</tr>
<tr>
<td>neutron</td>
<td>$1.67493 \times 10^{-27}$</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>electron</td>
<td>$0.00091 \times 10^{-27}$</td>
<td>0.0005486</td>
<td>-1</td>
</tr>
</tbody>
</table>
Mass Number, A

Atoms of the same element can differ in mass number

\[ A = \text{number of protons} + \text{number of neutrons} \]

<table>
<thead>
<tr>
<th>Isotope</th>
<th># Protons</th>
<th># Neutrons</th>
<th>Z</th>
<th>A</th>
<th>Symbol</th>
</tr>
</thead>
</table>
| Carbon-12   | 6         | 6          | 6 | 12 | ▏▏
| Carbon-14   | 6         | 8          | 6 | 14 | ▏▏

\[ a \neq b \neq c \neq d \neq e \neq f \neq g \neq h \neq i \neq j \neq k \neq l \neq m \neq n \neq o \neq p \neq q \neq r \neq s \neq t \neq u \neq v \neq w \neq x \neq y \neq z \]
Nuclei Representation

\[ ^A_Z E \]

\[ ^1_1 H \]
\[ ^2_1 H \]
\[ ^3_1 H \]

\[ A - Z = \text{number of neutrons} \]
Precise determination of the masses of individual atoms

The mass spectrometer

Beam of $^{37}\text{Cl}^+$ ions

Beam of $^{35}\text{Cl}^+$ ions
Mass spectrum of chlorine
**Atomic Mass from Isotopic Composition**

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Atomic Mass (amu)</th>
<th>Natural Abundance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ne-20</td>
<td>20.00</td>
<td>90.48</td>
</tr>
<tr>
<td>Ne-21</td>
<td>21.00</td>
<td>0.27</td>
</tr>
<tr>
<td>Ne-22</td>
<td>22.00</td>
<td>9.25</td>
</tr>
</tbody>
</table>

\[
A.M. = (A.M.\text{isotope}_1 \frac{\%}{100} + A.M.\text{isotope}_2 \frac{\%}{100} + \ldots)
\]
Meaning of Atomic Masses

A nickel atom is $58.69 / 40.08 = 1.464$ times as heavy as a calcium ion

It is $58.69 / 10.81 = 5.29$ times as heavy as a boron ion

<table>
<thead>
<tr>
<th>Element</th>
<th>B</th>
<th>Ca</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic Mass (amu)</td>
<td>10.81</td>
<td>40.08</td>
<td>58.69</td>
</tr>
</tbody>
</table>
Atomic Mass from Isotopic Composition

\[
\begin{align*}
20.00 \ (0.9048) \ + \\
21.00 \ (0.0027) \\
22.00 \ (0.0925)
\end{align*}
\]

\[20.18 \text{ amu}\]

\[
A.M. \ Ne = 20.18\text{g/mol}
\]
Meaning of Atomic Masses

• Give relative masses of atoms based on C–12 scale.

• The Most common isotope of carbon is assigned an atomic mass of 12 amu.

• The amu is defined as 1/12 of the mass of one neutral carbon atom

http://www.c14dating.com/int.html
For light ($Z < 20$) isotopes the stable ratio is 1.0; with heavier isotopes it increases to 1.5. There are no stable isotopes for elements of $Z > 83$ (Bi).
Ions

Formation of Monatomic Ions

Charges of Monatomic Ions

Polyatomic Ions

Formulas
Formation of Monatomic Ions

\[ \text{Na atom (11p}^+,11e^-) \rightarrow \text{Na}^+ \text{ ion (11p}^+,10e^-) + e^- \]

\[ \text{F atom (9p}^+,9e^-) + e^- \rightarrow \text{F}^- \text{ ion (9p}^+,10e^-) \]

Nucleus remains unchanged
Charges of some metallic ions (non-metals, anions)

<table>
<thead>
<tr>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>N³⁻</td>
<td>O²⁻</td>
<td>F⁻</td>
<td>Ne</td>
<td>H⁻</td>
<td>He</td>
</tr>
<tr>
<td>S²⁻</td>
<td>Cl⁻</td>
<td>Ar</td>
<td></td>
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<tr>
<td>Se²⁻</td>
<td>Br⁻</td>
<td>Kr</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Te²⁻</td>
<td>I⁻</td>
<td>Xe</td>
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<td></td>
<td>Rn</td>
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</table>
Charges of some metallic ions (metals, cations)

<table>
<thead>
<tr>
<th></th>
<th>Li⁺</th>
<th>Na⁺</th>
<th>K⁺</th>
<th>Rb⁺</th>
<th>Cs⁺</th>
<th>Ca²⁺</th>
<th>Sr²⁺</th>
<th>Ba²⁺</th>
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<tbody>
<tr>
<td>1</td>
<td></td>
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<tr>
<td>2</td>
<td>Li⁺</td>
<td>Na⁺</td>
<td>K⁺</td>
<td>Rb⁺</td>
<td>Cs⁺</td>
<td>Ca²⁺</td>
<td>Sr²⁺</td>
<td>Ba²⁺</td>
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<td></td>
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<td>12</td>
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<tr>
<td>15</td>
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<td></td>
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<td></td>
</tr>
</tbody>
</table>

- Al³⁺
- Cr³⁺
- Mn²⁺
- Fe²⁺
- Fe³⁺
- Co²⁺
- Ni²⁺
- Cu⁺
- Cu²⁺
- Zn²⁺
- Ag⁺
- Cd²⁺
- Sn²⁺
- Pb²⁺
- Bi³⁺
Polyatomic Ions

Names and formulas

General structure
## Polyatomic Ions

<table>
<thead>
<tr>
<th>Cations</th>
<th>Anions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonium</td>
<td>Permanganate</td>
</tr>
<tr>
<td>$\text{NH}_4^+$</td>
<td>$\text{MnO}_4^-$</td>
</tr>
<tr>
<td>Mercury(I)</td>
<td>Peroxide</td>
</tr>
<tr>
<td>$\text{Hg}_2^{+2}$</td>
<td>$\text{O}_2^{2-}$</td>
</tr>
<tr>
<td></td>
<td>Acetate</td>
</tr>
<tr>
<td></td>
<td>$\text{C}_2\text{H}_3\text{O}_2^-$</td>
</tr>
</tbody>
</table>
The prefixes and suffixes used to name oxyanions are related to the valence of the element contained in the formula

<table>
<thead>
<tr>
<th>per-</th>
<th>-ate</th>
<th>-ate</th>
<th>-ite</th>
<th>hypo-</th>
<th>-ite</th>
</tr>
</thead>
<tbody>
<tr>
<td>XO_4^-</td>
<td>XO_3^-</td>
<td>XO_2^-</td>
<td></td>
<td>XO^-</td>
<td></td>
</tr>
</tbody>
</table>

Ex:
- Potassium Permanganate: KMnO_4
- Potassium Manganate: KMnO_3
- Ammonium hypochlorite: NH_4ClO
- Mercury(I) iodite: (Hg_2)(IO_2)_2
- Mercury(II) bromate: Hg(BrO_3)_2
- Iron(III) periodate: Fe(IO_4)_3
Writing Ionic Compound Formulas

Apply principle of electrical neutrality

<table>
<thead>
<tr>
<th>Cation</th>
<th>Anion</th>
<th>peroxide</th>
<th>oxide</th>
<th>dichromate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cation</td>
<td>HCO$_3^-$</td>
<td>O$_2^{2-}$</td>
<td>O$^2-$</td>
<td>Cr$_2$O$_7^{2-}$</td>
</tr>
<tr>
<td>Ammonium NH$_4^+$</td>
<td>NH$_4$HCO$_3$</td>
<td>(NH$_4$)$_2$O$_2$</td>
<td>(NH$_4$)$_2$O</td>
<td>(NH$_4$)$_2$Cr$_2$O$_7$</td>
</tr>
<tr>
<td>Mercury(I) Hg$_2^{2+}$</td>
<td>Hg$_2$(HCO$_3$)$_2$</td>
<td>Hg$_2$O$_2$</td>
<td>Hg$_2$O</td>
<td>Hg$_2$Cr$_2$O$_7$</td>
</tr>
<tr>
<td>Sodium Na$^+$</td>
<td>NaHCO$_3$</td>
<td>Na$_2$O$_2$</td>
<td>Na$_2$O</td>
<td>Na$_2$Cr$_2$O$_7$</td>
</tr>
<tr>
<td>Calcium Ca$^{2+}$</td>
<td>Ca(HCO$_3$)$_2$</td>
<td>CaO$_2$</td>
<td>CaO</td>
<td>Ca Cr$_2$O$_7$</td>
</tr>
</tbody>
</table>
Naming Ionic Compounds

Name cation followed by anion

For transition metals cations the charge is indicated by Roman numeral when using the Stock system

\[
\begin{align*}
\text{NH}_4\text{Br} & \quad \text{ammonium bromide} \\
\text{Na}_2\text{SO}_4 & \quad \text{sodium sulfate} \\
\text{Fe(}\text{NO}_3\text{)}_3 & \quad \text{iron (III) nitrate}
\end{align*}
\]
### Oxoanions of nitrogen, sulfur and chlorine

<table>
<thead>
<tr>
<th>Nitrogen</th>
<th>Sulfur</th>
<th>Chlorine</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{NO}_3^-$ nitrate</td>
<td>$\text{SO}_4^{2-}$ sulfate</td>
<td>$\text{ClO}_4^-$ perchlorate</td>
</tr>
<tr>
<td>$\text{NO}_2^-$ nitrite</td>
<td>$\text{SO}_3^{2-}$ sulfite</td>
<td>$\text{ClO}_3^-$ chlorate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\text{ClO}_2^-$ chlorite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\text{ClO}^-$ hypochlorite</td>
</tr>
</tbody>
</table>
### Greek prefixes used in nomenclature

<table>
<thead>
<tr>
<th>Number</th>
<th>Prefix</th>
<th>Number</th>
<th>Prefix</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>di</td>
<td>6</td>
<td>hexa</td>
</tr>
<tr>
<td>3</td>
<td>tri</td>
<td>7</td>
<td>hepta</td>
</tr>
<tr>
<td>4</td>
<td>tetra</td>
<td>8</td>
<td>octo</td>
</tr>
<tr>
<td>5</td>
<td>penta</td>
<td>9</td>
<td>nona</td>
</tr>
</tbody>
</table>

*The prefix mono (1) is seldom used*

<table>
<thead>
<tr>
<th>Number</th>
<th>Prefix</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>deca</td>
</tr>
</tbody>
</table>
Binary Molecular Compounds

Use of Greek prefixes

$\text{SF}_6$  sulfur hexafluoride

$\text{N}_2\text{O}_3$  dinitrogen trioxide

$\text{H}_2\text{O}$  dihydrogen monoxide
Types of Acids

• Binary Acids:
  – hydrochloric acid

• Oxoacids:
  – ate salt ic acid

• Examples:
  – $\text{HClO}_4$ hyperchloric acid
  – $\text{Ca(ClO}_4\text{)}_2$ calcium perchlorate
Binary Compounds

Usually end in -ide

Two nonmetals

Metal/nonmetal

Hydrogen/nonmetal

Metal with one type of cation

Metal with varying type of cations

Determine charge of cation

1. choose appropriate -ous or -ic ending on metal
2. stem name of metal -ide

1. name metal
2. name nonmetal

1. use roman numeral
2. stem name of nonmetal, -ide

1. Hydrogen
2. Name nonmetal

prefix that indicate # atoms for ea. element

in water

1. prefix hydro-
2. suffix -ic

not in water

1. add word acid

prefix that indicate # atoms for ea. element