Early Atomic Theories and the Origins of Quantum Theory

Chapter 3.1
What is Matter Made of?

- People have wondered about the answer to this question for thousands of years
Philosophers

Democritus vs. Aristotle

Matter is composed of tiny, indivisible particles called atoms

All matter is made of four elements: earth, air, fire, and water
Philosophy and Science

- **Philosophers** come up with their ideas based on intuition and reason

- **Scientists** come up with their ideas through experimentation using tools and technology
John Dalton

Dalton’s atomic theory was based on the experimental work of many other scientists who used instruments that were invented to precisely measure mass and volume:

1) **The Law of Conservation of Mass** – Antoine Lavoisier
   “Matter can not be created or destroyed.”

2) **The Law of Definite Proportions** – Joseph Proust
   “A given compound always contains exactly the same proportion of elements by mass.”
   EX: oxygen makes up about \( \frac{8}{9} \) of the mass of any sample of pure water, while hydrogen makes up the remaining \( \frac{1}{9} \) of the mass.

3) **The Law of Multiple Proportions** – John Dalton
   “When two elements form a series of compounds, the ratios of the masses of the second element that combine with 1 gram of the first element can always be reduced to small whole numbers.”
   EX: A fixed mass of carbon, say 100 grams, may react with 133 grams of oxygen to produce one oxide, or with 266 grams of oxygen to produce the other. The ratio of the masses of oxygen that can react with 100 grams of carbon is 266:133 \( \approx \) 2:1, a ratio of small whole numbers.
Dalton’s Atomic Theory

• All matter is made up of indivisible particles called atoms

• Atoms of the same element are identical, and atoms of different elements are different

• Chemical compounds are formed when atoms combine with each other

• Chemical reactions involve reorganization of atoms, but the atoms themselves can not be created or destroyed
Dalton’s Model of the Atom

Billiard Ball

The atom is a featureless sphere
J.J. Thomson

Thomson’s atomic theory was also based on the experimental work of many other scientists who also used technology to make their observations.

1) **Arrhenius** – studied the electrical nature of acids and bases and discovered that atoms form ions in solution.

2) **Faraday** – worked with electricity and solutions and discovered that particular atoms and ions gain or lose a specific amount of charge.
J.J. Thomson

3) **Crookes** – Used Cathode Ray Tubes (Electric Discharge Tubes) to demonstrate that electricity is composed of negatively charged particles
4) **Millikan** – Used his charged oil drop experiment to calculate the mass of an electron to be $9.11 \times 10^{-31}$ kg
Thomson’s Experiment

• He used the cathode ray tube

• Determined that the ray was composed of a stream of negatively charged particles which he called electrons

• Measured the deflection of the beam and was able to determine the charge-to-mass ratio of an electron

\[ e = -1.76 \times 10^8 \text{C/g} \]

• Reasoned that since atoms are electrically neutral, they must also contain a positive charge
Thomson’s Model of the Atom

Plum Pudding
(or Blueberry Muffin)

(a) spherical cloud of positive charge
(b) electrons

[Image of Thomson]
Ernest Rutherford

• Rutherford’s atomic theory was also based on the experimental work of other scientists and was dependent on improved experimental technology
• Henri Becquerel was responsible for early research on radioactivity
• **Radioactivity** is the spontaneous decay or disintegration of the nucleus of an atom
• This led to Rutherford’s discovery of the **alpha particle** (a small, dense, positively charged particle that is a type of radioactive emission)
Rutherford’s Famous Gold Foil Experiment

- Positively charged alpha particles were fired at a thin sheet of gold foil
Rutherford’s Hypothesis

This is what he expected to see:

This is his reasoning:
Rutherford’s Results

This is what he actually observed:

This is what he concluded:
• Most of the atom is empty space
• All of the positive charge of the atom (the protons) are concentrated in a dense central region (the nucleus)
Rutherford’s Model of the Atom

Beehive

• A dense positive centre called the nucleus where most of the mass of the atom is located

• A cloud of negatively charged electrons swarming around the nucleus
Atoms and Isotopes

- Subatomic Particles Review:

<table>
<thead>
<tr>
<th>NAME</th>
<th>SYMBOL</th>
<th>CHARGE</th>
<th>MASS (AMU)</th>
<th>MASS (G)</th>
<th>LOCATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>proton</td>
<td>p⁺</td>
<td>1+</td>
<td>1.007</td>
<td>1.673 x 10⁻²⁴</td>
<td>nucleus</td>
</tr>
<tr>
<td>neutron</td>
<td>n⁰</td>
<td>0</td>
<td>1.009</td>
<td>1.675 x 10⁻²⁴</td>
<td>nucleus</td>
</tr>
<tr>
<td>electron</td>
<td>e⁻</td>
<td>1−</td>
<td>5.486 x 10⁻⁴</td>
<td>9.109 x 10⁻²⁸</td>
<td>outside nucleus</td>
</tr>
</tbody>
</table>
Atoms and Isotopes

• The **Atomic Number (Z)** is the number of protons in the nucleus.
• The number of protons is what makes atoms of each element unique.
• Since atoms are electrically neutral, they have the same number of protons and electrons.
• The number of electrons in an atom, and their arrangement determine the physical properties and chemical behaviour of the atom.
• **Mass Number (A)** is the total number of protons and neutrons in the nucleus.

### ATOMIC SYMBOLS  
*e.g., “carbon twelve”*

- **“A”** Mass number
  
  \[ \# p^+ + \# n^0 \]

- **“Z”** Atomic number
  
  \[ \# p^+ (= \# e^-) \]

- ¹²C

- Element symbol
Atoms and Isotopes

- Two atoms with the same number of protons but different number of neutrons are called **isotopes**

![Diagram showing the nucleus with 11 protons, 12 neutrons, and 11 electrons for Na-23 and Na-24 isotope]

- A **radioisotope** is an isotope with an unstable nucleus that decays and emits gamma rays and/or subatomic particles
The Debate on Light

Isaac Newton: Light is a PARTICLE!

No! It’s not!
Light is a WAVE!

Christiaan Huygens
The Classical Theory of Light

- James Maxwell proposed that light could act on charged particles because it existed as an electromagnetic wave made of magnetic and electric fields.
The Classical Theory of Light

- Light is an electromagnetic wave composed of continuous wavelengths that form a spectrum.
The Photoelectric Effect

- Heinrich Hertz
- Electrons are emitted by matter that absorbs energy from shortwave electromagnetic radiation
The Photoelectric Effect

• Hertz’s experiments demonstrated that the colour of the light was most important in determining the energy of the emitted electrons.

• The classical theory of light could not explain these observations, so it began to be viewed as flawed.
Planck’s Quantum Hypothesis

• Max Planck conducted experiments where he heated solids to high temperatures causing them to glow different colours

Figure 14 A white-hot wire and a red-hot wire emit light at different colours and intensities. The light emitted does not follow the expected results of the classical theory of light.
Planck’s Quantum Hypothesis

• Planck postulated that matter can gain or lose energy, \( E \), only in whole number multiples according to the equation \( E=hf \)

• Where \( f \) is the frequency of radiation and \( h \) is Planck’s constant (6.63x10\(^{-24}\)J∙s)

One burst or packet of energy is known as a quantum of energy

A photon is a quantum of light energy
Einstein and Planck

Figure 3
Scientists used to think that as the intensity or brightness of light changes, the total energy increases continuously, like going up the slope of a smooth hill. As a consequence of Planck’s work, Einstein suggested that the slope is actually a staircase with tiny steps, where each step is a quantum of energy.
Einstein and Photons

• Einstein suggested that electromagnetic radiation could be viewed as a stream of particles called photons
• A photon is a quantum of light energy
• Einstein explained the photoelectric effect by proposing that an electron was emitted from the surface of the metal because a photon collided with the electron
• Some of the transferred energy caused the electron to break away from the atom, and the rest was converted to kinetic energy
• If a single electron absorbs a single photon with the right quantity of energy, the electron can escape the metal surface. If a photon does not have enough energy, no electrons can escape the metal no matter how many photons strike it
Einstein and Photons

**Figure 7**
Each photon of light has a different energy, represented by the relative sizes of the circles.

**Figure 8**
(a) Using a bowl analogy, different atoms would be represented with bowls of different depths.

(b) For most atoms, the energy of a red photon is not great enough to boost the electron (marble) out of the atom (bowl). The electron can absorb the energy but is still stuck in the atom. This process simply results in the heating of the sample.

(c) A higher-energy photon, such as a UV photon, has more than enough energy to boost the electron out of many atoms.

(a) 
\[
\begin{align*}
E & \quad e^- \quad K \\
& \quad e^- \quad Na \\
& \quad e^- \quad Li
\end{align*}
\]

(b) 
red photon \[\Rightarrow\] electron gains energy but is still trapped

(c) 
UV photon \[\Rightarrow\] electron escapes from atom
HOMEWORK

Required Reading:

p. 132-142
(remember to supplement your notes!)

Questions:

p. 142 #1-8, 10

"Of course the elements are earth, water, fire and air. But what about chromium? Surely you can't ignore chromium."