Chapters 31
Atomic Physics
Overview of Chapter 31

- Early Models of the Atom
- The Spectrum of Atomic Hydrogen
- Bohr’s Model of the Hydrogen Atom
- de Broglie Waves and the Bohr Model
- The Quantum Mechanical Hydrogen Atom
- Multi-electron atoms and the Periodic Table
- Atomic Radiation
31-1 Early Models of the Atom

• **Electron** was discovered in 1897, and was observed to be much smaller than the atom...

• First modern model of the atom was therefore the **“plum pudding” model**

• Tiny electrons embedded in a mass of positive charge.
31-1 Early Models of the Atom

- Experiments were done to confirm model..
  - Looked at how alpha particles (helium nuclei) scattered from gold foil…

- Found many more large-angle scatters than expected…
  - Something that could only happen if the positive charge were concentrated in a tiny volume…
  - Rather different to the plum pudding model.
31-1 Early Models of the Atom

This led to the “solar system” model of the atom – electrons orbiting a small, positively charged nucleus.
31-2 The Spectrum of Atomic Hydrogen

If we look at the light emitted by a low-pressure gas when subjected to a large electric field, we find a series of individual lines, called a line spectrum.
31-2 The Spectrum of Atomic Hydrogen

- Each atom has its own particular pattern of emission lines...

- If white light passes through atom, it absorbs the same frequencies seen in the emission spectrum....
31-2 The Spectrum of Atomic Hydrogen

Wavelengths in the visible spectrum of hydrogen are given by:

\[ \frac{1}{\lambda} = R \left( \frac{1}{2^2} - \frac{1}{n^2} \right) \quad n = 3, 4, 5, \ldots \]

\( R \) is the Rydberg constant:

\[ R = 1.097 \times 10^7 \text{ m}^{-1} \]

Called the Balmer series of spectral lines.
31-3 Bohr’s Model of the Hydrogen Atom

1. *Electron* in a hydrogen atom moves in a *circular orbit* around the nucleus...

2. Only certain orbits are allowed, where the angular momentum in the $n$th allowed orbit is

   $$ L_n = nh/2\pi $$

3. Radiation is emitted when an electron changes from one orbit to another, with frequency given by:

   $$ |\Delta E| = hf $$
31-3 Bohr’s Model of the Hydrogen Atom

In order for an electron to move in a circle of radius $r$ at speed $v$, the electrostatic force must provide the required centripetal force. Hence:

$$mv^2 = \frac{ke^2}{r}$$

Adding the angular momentum ($L=mvr$) constraint gives:

$$v_n = \frac{nh}{2\pi mnr_n} \quad n = 1, 2, 3, \ldots$$
Solving these equations for the allowed radii gives:

\[ r_n = \left( \frac{\hbar^2}{4\pi^2 m e^2} \right) n^2 \quad n = 1, 2, 3, \ldots \]

The quantity in parentheses is the radius of the smallest orbit:

\[ r_1 = 5.29 \times 10^{-11} \text{ m} \]
31-3 Bohr’s Model of the Hydrogen Atom

• Bohr’s model gives correct predictions for any single-electron atom, when the different Coulomb force is taken into account.

• Here, $Z$ is the number of protons in the nucleus:

$$r_n = \left( \frac{\hbar^2}{4\pi^2 mkZe^2} \right) n^2 \quad n = 1, 2, 3, \ldots$$
31-3 Bohr’s Model of the Hydrogen Atom

- Total mechanical energy of an electron in a Bohr orbit is the sum of its kinetic and potential energies.

\[
E_n = -(13.6 \text{ eV}) \frac{Z^2}{n^2} \quad n = 1, 2, 3, \ldots
\]

- Lowest energy is called the ground state.
  - Most atoms at room temperature are in the ground state…
31-3 Bohr’s Model of the Hydrogen Atom

- If we assume that the radiation emitted from excited atoms corresponds to the energy difference between two levels:

\[ \frac{1}{\lambda} = \left( \frac{2\pi^2 mk^2 e^4}{h^3 c} \right) \left( \frac{1}{n_f^2} - \frac{1}{n_i^2} \right) \]

- When numerical values are substituted for the constants in the parentheses, they yield Rydberg’s constant:

\[ R = 1.097 \times 10^7 \text{ m}^{-1} \]
De Broglie proposed that the allowed orbits were those which of the electron...
31-4 de Broglie Waves and the Bohr Model

Therefore, the momentum of an electron in the $n$th orbit is:

\[
p = mv = \frac{h}{\lambda} = \frac{h}{(2\pi r/n)} = \frac{nh}{2\pi r} \quad n = 1, 2, 3, \ldots
\]

And the angular momentum:

\[
L = rmv = \frac{nh}{2\pi} \quad n = 1, 2, 3, \ldots
\]

Exactly as Bohr stated…
The quantum mechanical description of the atom requires four numbers:

1. The principal quantum number, \( n \), gives the energy of the electron.

\[
E = \frac{(-13.6 \text{ eV})}{n^2}
\]

2. The orbital angular momentum quantum number \( \ell \):

\[
L = \sqrt{\ell (\ell + 1)} \frac{h}{2\pi}
\]

\( \ell = 0, 1, 2, \ldots, (n - 1) \)
3. The magnetic quantum number, which comes into play if there is a magnetic field:

\[ m_\ell = -\ell, -\ell + 1, -\ell + 2, \ldots, -1, 0, 1, \ldots, \ell - 2, \ell - 1, \ell \]

\[ L_z = m_\ell \frac{h}{2\pi} \]

4. The electron spin number, which is an intrinsic property of the electron:

\[ m_s = -\frac{1}{2}, \frac{1}{2} \]
A state is defined as a particular assignment of the four quantum numbers:

<table>
<thead>
<tr>
<th>$n$, $\ell$</th>
<th>$\ell$</th>
<th>$m_\ell$</th>
<th>$m_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n = 1$, $\ell = 0$</td>
<td>$0$</td>
<td>$0$</td>
<td>$\frac{1}{2}$, $-\frac{1}{2}$</td>
</tr>
<tr>
<td>$n = 2$, $\ell = 0$</td>
<td>$0$</td>
<td>$0$</td>
<td>$\frac{1}{2}$, $-\frac{1}{2}$</td>
</tr>
<tr>
<td>$n = 2$, $\ell = 1$</td>
<td>$1$</td>
<td>$1$, $0$, $-1$</td>
<td>$\frac{1}{2}$, $-\frac{1}{2}$</td>
</tr>
</tbody>
</table>
31-6 Multi-electron Atoms and the Periodic Table

- Atoms with multiple electrons are more complex, and there are no simple formulas for the energy levels.

- They are still characterized by the same quantum numbers.
31-6 Multi-electron Atoms and the Periodic Table

Pauli exclusion principle states that only one electron may be in each quantum state:

1. Only one electron at a time may have a particular set of quantum numbers, $n$, $\ell$, $m_\ell$ and $m_s$.

2. Once a particular state is occupied, other electrons are excluded from that state.

Therefore, if electrons are added to an atom, they must go into higher and higher energy states.
31-6 Multi-electron Atoms and the Periodic Table

Each energy level can accommodate a certain number of electrons, depending on $n$. 

![Energy Level Diagram](image)
The electron arrangements are given here for the first eight elements of the periodic table:
A shorthand notation has been devised to describe the configuration of electrons in a particular atom. Diagram shows how to describe a single energy level.
Once every occupied level is described in this way, we have a complete description of the electron configuration of the atom.

<table>
<thead>
<tr>
<th>Atomic number</th>
<th>Element</th>
<th>Electronic configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hydrogen (H)</td>
<td>1s(^1)</td>
</tr>
<tr>
<td>2</td>
<td>Helium (He)</td>
<td>1s(^2)</td>
</tr>
<tr>
<td>3</td>
<td>Lithium (Li)</td>
<td>1s(^2) 2s(^1)</td>
</tr>
<tr>
<td>4</td>
<td>Beryllium (Be)</td>
<td>1s(^2) 2s(^2)</td>
</tr>
<tr>
<td>5</td>
<td>Boron (B)</td>
<td>1s(^2) 2s(^2) 2p(^1)</td>
</tr>
<tr>
<td>6</td>
<td>Carbon (C)</td>
<td>1s(^2) 2s(^2) 2p(^2)</td>
</tr>
<tr>
<td>7</td>
<td>Nitrogen (N)</td>
<td>1s(^2) 2s(^2) 2p(^3)</td>
</tr>
<tr>
<td>8</td>
<td>Oxygen (O)</td>
<td>1s(^2) 2s(^2) 2p(^4)</td>
</tr>
<tr>
<td>9</td>
<td>Fluorine (F)</td>
<td>1s(^2) 2s(^2) 2p(^5)</td>
</tr>
</tbody>
</table>
31-7 Atomic Radiation

- X-rays are emitted when highly energetic electrons strike a metal target.

- If the electrons have enough energy, they can knock out a K-shell ($n = 1$) electron in a multi-electron atom…
X-rays are used for medical imaging, among other applications.
31-7 Atomic Radiation

The energy of a K-shell electron is given by:

$$E_K = - (13.6 \text{ eV}) \frac{(Z - 1)^2}{1^2}$$
31-7 Atomic Radiation

The word “laser” is an acronym for light amplification by the stimulated emission of radiation.

Spontaneous emission occurs when an electron in an excited state drops to a lower state, emitting a photon in the process. The photons are emitted in random directions.
31-7 Atomic Radiation

Stimulated emission occurs when the atom is bombarded with photons of the emission wavelength; this stimulates the transition to occur.
31-7 Atomic Radiation

- Stimulated emission is in the same direction as the incident photon, and the photons have the same phase.

- Since one incoming photon produces two outgoing photons, the light intensity is amplified....
The coherence of laser light is critical in the manufacture of holograms, as information is contained in the interference pattern.

Diagram:
- Laser
- Beam splitter
- Reference beam
- Object beam
- Object
- Interference pattern
- Film
31-7 Atomic Radiation

Fluorescence occurs when electrons emit photons of various frequencies when returning to the ground state.

• In fluorescence, ultraviolet light excites atoms into metastable states.

• They then decay in two or more steps, emitting visible light.
31-7 Atomic Radiation

This is an example of a fluorescent compound, green fluorescent protein (GFP).
3. Copper atoms have 29 protons in their nuclei. If the copper nucleus is a sphere with a diameter of $4.8 \times 10^{-15}$ m, find the work required to bring an alpha particle (charge = $+2e$) from rest at infinity to the “surface” of the nucleus.

Answer: 5.6 pJ
5. • Find the wavelength of the Balmer series spectral line corresponding to $n = 15$.

Answer: 369.7 nm
28. Applying the Bohr model to a triply ionized beryllium atom (Be\(^{3+}\), Z = 4), find (a) the shortest wavelength of the Lyman series for Be\(^{3+}\) and (b) the ionization energy required to remove the final electron in Be\(^{3+}\).

Answer: a) 5.697 nm
Answer: b) 218 eV
30. **IP** The kinetic energy of an electron in a particular Bohr orbit of hydrogen is $1.35 \times 10^{-19}$ J. (a) Which Bohr orbit does the electron occupy? (b) Suppose the electron moves away from the nucleus to the next higher Bohr orbit. Does the kinetic energy of the electron increase, decrease, or stay the same? Explain. (c) Calculate the kinetic energy of the electron in the orbit referred to in part (b).

Answer: a) $n=4$

Answer: b) Decrease

Answer: c) 0.544 eV
37. ** What is the radius of the hydrogen-atom Bohr orbit shown in Figure 31–30? **

**Answer:**

1.32 nm
46. **CE** How many electrons can occupy (a) the 2p subshell and (b) the 3p subshell?

Answer: a) 6
Answer: b) 6
62. Using the Bohr model, estimate the energy of a $K_{\alpha}$ X-ray emitted by lead ($Z = 82$).

Answer: 66.9 KeV