Many Electrons + Pauli Exclusion Principle

Complex atom

Each $e^-$ - Four Quantum numbers

$n, \ell, m_\ell, m_s$

$n \geq 1$, $0 \leq \ell \leq n-1$, $|m_\ell| \leq \ell$, $m_s = \pm \frac{1}{2}$

NO TWO ELECTRONS CAN OCCUPY THE SAME QUANTUM STATE

If all $e^-$ in lowest state → ALL ELEMENTS ~ SAME
No Chemistry.

$U(r) = -\frac{Ze^2}{4\pi\varepsilon_0 r}$

$e^2 \rightarrow Ze^2$

$E_n = -\frac{1}{(4\pi\varepsilon_0)^2} \frac{mZe^4}{2\hbar^2} (\frac{1}{n^2})$

$= -\frac{Z^2}{n^2} (13.6) eV$
# Electron Shells

<table>
<thead>
<tr>
<th>n</th>
<th>l</th>
<th>me</th>
<th>Notation</th>
<th># states</th>
<th>Shell</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1s</td>
<td>2</td>
<td>K</td>
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<tr>
<td>2</td>
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<td>0</td>
<td>2s</td>
<td>27 8</td>
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<tr>
<td>2</td>
<td>1</td>
<td>-1,0,1</td>
<td>2p</td>
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<td>3</td>
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<td>3s</td>
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<td>-2,-1,0,1,2</td>
<td>3d</td>
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<td>4</td>
<td>0</td>
<td>0</td>
<td>4s</td>
<td>2 32</td>
<td>N</td>
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<tr>
<td>4</td>
<td>1</td>
<td>-1,0,1</td>
<td>4p</td>
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<td>2</td>
<td>-2,-1,0,1,2</td>
<td>4d</td>
<td>10</td>
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<tr>
<td>3</td>
<td>-3 +3</td>
<td>4f</td>
<td>14</td>
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</tbody>
</table>
Ne. $Z = 10$

Filled L shell - Chemically inert

$1s^2 2s^2 2p^6$

2s

2p

F $Z = 9$

Strong Affinity to attract electrons +
Fill shell. Highly reactive

$F + e^- \rightarrow F^-$ Filled shell
Na $Z = 11$

\(1s^2\ 2s^2\ 2p^6\ 3s^2\)

\(3s\uparrow\quad 2s\uparrow\uparrow\uparrow\downarrow\downarrow\downarrow\downarrow\ 2p\)

\(1s\uparrow\uparrow\)

\(3s\)

\(3d\)

\(4s\)

Filled shell + 1e$^-$

Highly reactive

Na $\rightarrow$ Na$^+$ + e$^-$

\(Z_{\text{eff}} = 11-10 = 1\)

\(E_n = -\frac{Z_{\text{eff}}^2 (13.6)}{n^2}\ eV\)

\(E_{3s} = -5.138\ eV\)

\(E_{3p} = -3.035\ eV\)

\(E_{3d} = -1.521\ eV\)

\(E_{4s} = -1.947\ eV\)

\(3s\) penetrates into filled shell

$\Rightarrow$ higher $Z_{\text{eff}}$

\(V_{\text{eff}} = -\frac{e^2 Z_{\text{eff}}}{4\pi\epsilon_0 r}\)

\(11 - 2 - 8 = Z_{\text{eff}} = 1\)
This is the basis of the Periodic Table.

<table>
<thead>
<tr>
<th>3s</th>
<th>2s</th>
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<tbody>
<tr>
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<td>Li</td>
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<td>Be</td>
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- **FILLED SHELL.**
- **CHEMICALLY INERT**
- Loosely bound 2s e⁻.
- $\Delta E = 5.4eV$
- Alkali metal

<table>
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<td></td>
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<td>B</td>
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<td></td>
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<td>C</td>
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</tbody>
</table>

$1s^2 \ 2s^2 \ 2p$
X-Ray Spectra

\[ I(\lambda) \]

- 50kV
- 40kV
- 30kV
- 20kV

\[ \lambda_{\text{min}} = \frac{hc}{eV_{\text{ac}}} = \frac{1240 \text{ nm - eV}}{E(\text{eV})} \]

**Example:**

\[ \lambda_{\text{min}} = \frac{1240}{50 \times 10^3} = 2.48 \times 10^{-2} \text{ nm} = 24.8 \text{ pm} \]

- (L → K)
- (M → K)

\[ \begin{align*}
E_i &= -\left(\frac{Z-1}{2}\right)(13.6) = -(Z-1)(3.48 \text{ eV}) \\
E_f &= -\left(\frac{Z-1}{1}\right)(13.6) = -(Z-1)(13.6 \text{ eV}) \\
E_{ka} &= (Z-1)^2 10.2 \text{ eV}
\end{align*} \]

\[ f = \frac{E}{h} = \frac{(Z-1)^2 10.2}{4.136 \times 10^{-15} \text{ eV s}} = 2.47 \times 10^{15} \text{ Hz} (Z-1)^2 \]

Moseley 1913.
The conventional emission of light by an atom is called "spontaneous emission", and in this case, the direction & phase of the emitted light are random.

**Stimulated Emission** is the emission of a photon in response to the arrival of a photon of matching frequency. In this process, the emitted photon has precisely the same frequency, phase & direction as the incoming photon. This "light amplification" effect is the basis of the operation of a laser.
Population Inversion

Under conventional thermal conditions, there is negligible excitation of atoms into their excited states. According to Boltzmann's distribution

\[ n_g = \# \text{ atoms in ground state } = Ae^{-E_g/k_BT} \]
\[ n_{ex} = \# \text{ atoms in excited state } = Ae^{-E_{ex}/k_BT} \]

\[ \frac{n_{ex}}{n_g} = e^{-(E_{ex}-E_g)/k_BT} \]

E.g. if \( E_{ex}-E_g = 2eV = 3.2 \times 10^{-19} \text{ J} \approx 620 \text{ nm photon (visible)} \)

at \( T = 3000 \text{ K} \)

\[ \frac{E_{ex}-E_g}{k_BT} = \frac{3.2 \times 10^{-19} \text{ J}}{1.38 \times 10^{-23} \times (3000 \text{ K})} = 7.73 \]

\[ e^{-(E_{ex}-E_g)/k_BT} = e^{-7.73} = 4.4 \times 10^{-4} \]
To obtain a significant "population inversion", one must pump the atom into an excited state, e.g. He-Ne laser.

- Semiconductors laser (p-n)
- CO₂
- Chemical laser
- Magnetron - microwaves