CHAPTER 11

STATES OF MATTER AND INTERMOLECULAR FORCES

THE 3 STATES OF MATTER

**GAS** - FAST, ENERGETIC MOLECULES, NEARLY NO INTERMOLECULAR FORCES, NEITHER FIXED VOLUME OR SHAPE, COMPRESSIBLE

**LIQUID** - MOLECULES ARE CLOSE TOGETHER, INTERMOLECULAR FORCES STRONG ENOUGH TO HOLD A FIXED VOLUME, BUT WEAK ENOUGH TO ALLOW FLOW INTO ANY SHAPE

**SOLID** - MOLECULES IN DIRECT CONTACT, STRONG INTERMOLECULAR FORCES FIX SHAPE AND VOLUME. HARD TO COMPRESS

PHASE CHANGES

\[ \text{GAS} \xrightleftharpoons{\text{VAPORIZATION}} \text{LIQUID} \xrightleftharpoons{\text{CONDENSATION}} \]
\[ \text{LIQUID} \xrightleftharpoons{\text{FREEZING}} \text{SOLID} \xrightleftharpoons{\text{MELTING}} \]
\[ \text{GAS} \xrightarrow{\text{DEPOSITION}} \text{SOLID} \xrightarrow{\text{SUBLIMATION}} \]

**VAPORIZATION**

WHEN HEATED, A LIQUID GAINS ENOUGH KINETIC ENERGY TO BOIL, OR VAPORIZE. \( \Delta H_{vap} \) HEAT OF VAPORIZATION

\( \Delta H_{vap} \) IS DIFFERENT FOR EACH TYPE OF MOLECULE.

MOLECULES WITH STRONG INTERMOLECULAR FORCES REQUIRE MORE ENERGY TO BREAK FREE OF THE LIQUID STATE

\[ \text{LIQUID} \xrightarrow{\Delta H_{vap}} \text{GAS} \]
\[ \Delta H_{vap} = -\Delta H_{cond} \]

**EXAMPLE CALCULATION**

HOW MANY KJ DOES IT TAKE TO BOIL (VAPORIZE) 1 L OF \( \text{H}_2\text{O} \)?

\( \Delta H_{vap} = 44.0 \text{ KJ/mol} \) FOR \( \text{H}_2\text{O} \)
\[
\frac{1000 \text{ g}}{18 \text{ g/mol}} = 55.5 \text{ mol} \times 44.0 \text{ kJ/mol} = 2442 \text{ kJ}
\]

**Vapor Pressure**

*Defined as the partial pressure of a liquid's vapor when liquid and vapor are in equilibrium.*

The vapor pressure of a liquid is temperature dependent.

**Example Calculation Using the Ideal Gas Law**

At 50°C, the vapor over a liquid H₂O sample contains 0.076 g H₂O per liter. What is the vapor pressure of H₂O at 50°C?

\[
\rho V = nRT \\
\rho = \frac{nRT}{V} = \frac{0.076 \text{ g}}{18 \text{ g/mol}} = 0.0042 \text{ mol}
\]

\[
\rho = 0.0042 \text{ mol} \times \frac{0.0821 \text{ L atm}}{\text{ mol K}} \times 348 \text{ K} = 0.12 \text{ atm}
\]

**Boiling Point**

*Vaporization occurs not only at the surface, but throughout the liquid.*

The normal B.P. is when the pressure = 1.0 atm

**The Critical Point**

*Heating a liquid in a closed container prevents boiling because the pressure keeps building.*

Eventually the vapor density increases to the point where liquid and vapor are indistinguishable.

This is the critical point, the critical temp, the critical press above this point a supercritical fluid exists.
PHASE CHANGES IN SOLIDS

In a solid, atoms or molecules have vibrational energy.
They vibrate around a fixed position.
As temperature increases, vibrations become stronger until they are strong enough to break the intermolecular forces. This is melting, or fusion.

\[
\text{Solid } \xrightarrow{\Delta H_{\text{fusion}}} \text{ Liquid } \xleftarrow{\Delta H_{\text{freedom}}}
\]

A solid may transition directly to a gas. This is sublimation.

\[
\Delta H_{\text{sublim}} = \Delta H_{\text{fusion}} + \Delta H_{\text{vap}} \quad \text{(by Hess's law)}
\]

The triple point is that point on a phase diagram where solid, liquid, and gas can coexist.

A phase diagram represents temperature and pressure conditions at which each phase exists.

Intermolecular forces:
- Are electrostatic - the + is attracted to the -
- Are all dipolar - a dipole has a + end and a - end
- Dipoles may be very small and temporary
- Or large and permanent
THE WEAKEST ATTRACTIVE FORCES ARE DISPERSION FORCES
IF A NONPOLAR MOLECULE IS POLARIZABLE, A COLLECTION
OF MOLECULES MAY BE HELD TOGETHER BY A CONTINUING SERIES
OF TEMPORARY, CORRELATED, INDUCED DIPOLES
THE GREATER THE POLARIZABILITY, THE STRONGER THE FORCES

\[ F_2, C_2, Br_2, I_2 I \] IS LARGE AND
B.P. -188°C -34°C 59°C 184°C POLARIZABLE

MOLECULAR SHAPE ALSO MATTERS

\[
\begin{align*}
H & H & H & H & H \\
H & \cdot & C & - & \cdot & C & - & \cdot & C & - & H \\
H & H & H & H & H
\end{align*}
\]
BP 36°C

\[
\begin{align*}
H & H & C & - & C & - & C & - & H \\
H & H & C & - & H & H \\
H & H
\end{align*}
\]
BP 95°C

POLAR MOLECULES HAVE PERMANENT DIPOLES
THIS RESULTS IN STRONGER DIPOLE ATTRACTIONS

\[ N_2 \quad NO \quad O_2 \]

<table>
<thead>
<tr>
<th>DIPOLAR</th>
<th>MOMENT</th>
<th>0</th>
<th>0.15</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP °K</td>
<td>77</td>
<td>121</td>
<td>90</td>
<td></td>
</tr>
</tbody>
</table>

HYDROGEN BONDS - THE STRONGEST OF DIPOLE ATTRACTIONS

ONLY WITH O-H, N-H

IN H_2O

\[
\begin{align*}
H & \cdot & O & - & H \ldots & O & - & H
\end{align*}
\]

STONG INTERMOLECULAR ATTRACTIONS
LEADS TO HIGH BOILING POINTS

COMPARISONS
- COMPARING NONPOLAR SUBSTANCES USE MOLAR MASS AND SHAPE
- COMPARING POLAR SUBSTANCES - MORE POLAR = MORE ATTRACTIVE FORCE
- IN GENERAL, FOR SIMILAR MOLAR MASSES, POLAR MEANS HIGHER B.P. THAN NON POLAR
- HYDROGEN BONDING - HIGHEST B.P. IF ALL (O-H OR N-H)
SOLID STRUCTURE

NETWORK COVALENT SOLIDS

THE ALLOTROPES OF CARBON - DIAMOND, GRAPHITE, BUCKYBALLS AND NANOTUBES

THE STRUCTURE OF CRYSTALS

A REGULAR ARRAY OF IONS HELD TOGETHER BY ELECTROSTATIC ATTRACTIONS

THE ATTRACTIVE FORCE BETWEEN A CATION AND AN ANION INCREASES AS THE CHARGES INCREASE AND AS THE IONIC RADIi DECREASE. LATTICE ENERGIES INCREASE ACCORDINGLY.

COMPARE MgO, NaCl, NbI3

UNIT CELLS - THE SMALLEST REPEATING UNIT IN A CRYSTAL

SIMPLE CUBIC
EIGHT ATOMS
AT THE CORNERS OF A CUBE
52.4% FULL
1 ATOM TOTAL

BODY-CENTERED CUBIC
ADD 1 ATOM IN THE CENTER OF THE CUBE
68% FULL
2 ATOMS TOTAL

FACE-CENTERED CUBIC
EVERY FACE HAS AN ATOM
74% FULL

ONLY IN THE SIMPLE CUBIC DO CORNER ATOMS TOUCH

IONIC STRUCTURES

DEPENDING ON THE RATIO OF RADIi \( \frac{R_c}{R_a} \)

\( \frac{R_c}{R_a} \) FROM 0.225 TO 0.414 → TETRAHEDRAL
0.414 TO 0.732 → OCTAHEDRAL
7.32 ↓ CUBIC
CHAPTER 11

SKILLS

HEATS OF VAPORIZATION

WORK WITH VAPORIZATION, IDEAL GAS LAW

DO CALCULATIONS AT PHASE CHANGES

USE PHASE DIAGRAMS

INTERMOLECULAR FORCES

CRYSTAL STRUCTURES

NOT COVERED

SURFACE TENSION

PROBLEMS

EX 1.1, 27, 29

EX 11.3, 37, 39

EXERCISE 11.5, 47, 49

EX 11.5, 53

EX 11.6, EX 11.7

59, 61, 63

EX 11.8, EX 11.9

73, 75