CHAPTER ELEVEN
INTERMOLECULAR FORCES
AND LIQUIDS AND SOLIDS

KINETIC MOLECULAR THEORY
OF LIQUIDS AND SOLIDS

- Differences between condensed states and gases?

<table>
<thead>
<tr>
<th>Characteristic Properties of Gases, Liquids, and Solids</th>
</tr>
</thead>
<tbody>
<tr>
<td>State of Matter</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>Gas</td>
</tr>
<tr>
<td>Liquid</td>
</tr>
<tr>
<td>Solid</td>
</tr>
</tbody>
</table>

- Phase
  - Homogeneous part of a system
  - In contact with other parts
  - Separated by well-defined boundary
INTERMOLECULAR FORCES

- Not *Intra*molecular forces (Chap 9 & 10), but attractive forces between molecules.
- Responsible for:
  - Nonideal behavior in gases
  - Existence of condensed states
  - Bulk properties (i.e., BP)

INTERMOLECULAR FORCES

- van der Waals forces:
  - Dipole-dipole
  - Induced dipole
    - Dipole-induced
    - Ion-induced
  - Dispersion forces
- Ion-dipole
- Hydrogen bonding

INTERMOLECULAR FORCES

- Dipole-dipole
  - Polar molecules (possess dipole moments)
  - Larger dipole moment,
    Orientation of Polar Molecules in a Solid
INTERMOLECULAR FORCES

- Induced-Dipole (Nonpolar)
  - By ion or dipole
  - Depends on

- Dispersion forces
  - Nonpolar molecules

<table>
<thead>
<tr>
<th>Compound</th>
<th>Melting Point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₄</td>
<td>-182.5</td>
</tr>
<tr>
<td>CF₄</td>
<td>-150.0</td>
</tr>
<tr>
<td>CCl₄</td>
<td>-23.0</td>
</tr>
<tr>
<td>CBr₄</td>
<td>90.0</td>
</tr>
<tr>
<td>CI₄</td>
<td>171.0</td>
</tr>
</tbody>
</table>

Dispersion forces exist among ALL species!!
What type(s) of intermolecular forces exist between each of the following molecules?

HBr

\[ \text{CH}_4 \]

\[ \text{SO}_2 \]

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**INTERMOLECULAR FORCES**

- **Ion-Dipole**
  - Attraction between an ion and a polar species
  - Ion-Dipole Interaction

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**INTERMOLECULAR FORCES**

- **Weak interaction**
  - \[ \text{Na}^+ \]
  - \[ \text{Mg}^{2+} \]

- **Strong interaction**

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INTERMOLECULAR FORCES

Hydrogen Bonding
- Special type of dipole-dipole
- X-H; X =
- X-H — X-H
- Evidence of H-bonding
  » Compare BP of H compds of Groups 5A, 6A, and 7A
- Strength determined by

INTERMOLECULAR FORCES

INTERMOLECULAR FORCES

INTERMOLECULAR FORCES
PROPERTIES OF LIQUIDS

**Surface tension** is the amount of energy required to stretch or increase the surface of a liquid by a unit area.

Strong intermolecular forces

**Cohesion** is the intermolecular attraction between like molecules

**Adhesion** is an attraction between unlike molecules

**Viscosity** is a measure of a fluid’s resistance to flow.

<table>
<thead>
<tr>
<th>Table 11.3</th>
<th>Viscosity of Some Common Liquids at 20°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid</td>
<td>Viscosity (N·s/m²)</td>
</tr>
<tr>
<td>Acetone (C₆H₅O)</td>
<td>3.30 × 10⁻²</td>
</tr>
<tr>
<td>Benzene (C₆H₆)</td>
<td>6.25 × 10⁻²</td>
</tr>
<tr>
<td>Blood</td>
<td>8 × 10⁻²</td>
</tr>
<tr>
<td>Carbon tetrachloride (CCl₄)</td>
<td>9.00 × 10⁻²</td>
</tr>
<tr>
<td>Ethanol (C₂H₅OH)</td>
<td>1.20 × 10⁻⁵</td>
</tr>
<tr>
<td>Diethyl ether (C₆H₁₂O₂)</td>
<td>2.39 × 10⁻⁵</td>
</tr>
<tr>
<td>Glycerin (C₃H₈O₃)</td>
<td>1.49</td>
</tr>
<tr>
<td>Mercury (Hg)</td>
<td>1.33 × 10⁻⁷</td>
</tr>
<tr>
<td>Water (H₂O)</td>
<td>1.00 × 10⁻⁵</td>
</tr>
</tbody>
</table>
Water

Water is a unique substance

3-D Structure of Ice

Density of Water

CRYSTAL STRUCTURE

A crystalline solid possesses rigid and long-range order. In a crystalline solid, atoms, molecules or ions occupy specific (predictable) positions.

An amorphous solid does not possess a well-defined arrangement and long-range molecular order.

A unit cell is the

At lattice points:

Unit Cell    Unit cells in 3 dimensions

Seven Types of Unit Cells

Simple cubic

$\alpha = \beta = \gamma = 90^\circ$

Tetragonal

$\alpha = \beta = \gamma = 90^\circ$

Orthorhombic

$\alpha = \beta = \gamma = 90^\circ$

Rhombohedral

$\alpha = \beta = \gamma = 90^\circ$

Monoclinic

$\alpha = \beta = \gamma = 90^\circ, \beta \neq \gamma$

Triclinic

$\alpha \neq \beta \neq \gamma \neq 90^\circ$

Hexagonal

$\alpha = \beta = 90^\circ, \gamma = 120^\circ$
CRYSTAL STRUCTURE
(Packing)

- Different ways to pack identical spheres
- Determines which type of unit cell

Three Types of Cubic Cells

(a) Simple cubic
(b) Body-centered cubic
(c) Face-centered cubic

CRYSTAL STRUCTURE
(Packing)

- Simple Cubic Cell (scc)
  - Layers all the same
  - CN =

(a) (b) (c)

CRYSTAL STRUCTURE
(Packing)

- Body-Centered Cubic Cell (bcc)
  - Layers in depressions of previous
  - CN =

(a) (b) (c)
CRYSTAL STRUCTURE
(Packing)

- Face-Centered Cubic Cell (fcc)
  - Lattice point on each face of cube (6)
  - CN =
  - Diagrams of simple cubic, body-centered cubic, and face-centered cubic structures.

CRYSTAL STRUCTURE
(Closest Packing)

- Diagrams showing closest packing arrangements.
- Exploded views of hexagonal close-packed and cubic close-packed structures.

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X-RAY DIFFRACTION

- Scattering of X-rays by crystalline solid
- Diffraction pattern used to deduce arrangement of particles in the lattice

Arrangement for Obtaining the X-Ray Diffraction Pattern of a Crystal

TYPES OF CRYSTALS

- Ionic
- Covalent
- Molecular
- Metallic

Ionic Crystals
- Lattice points occupied by
- Held together by
- Hard, brittle, high melting point
- Poor conductor of heat and electricity

NaCl
**TYPES OF CRYSTALS**

Covalent Crystals
- Lattice points occupied by
- Held together by
- Hard, high melting point
- Poor conductor of heat and electricity

![Diamond and Graphite Diagram]

Molecular Crystals
- Lattice points occupied by
- Held together by
- Soft, low melting point
- Poor conductor of heat and electricity

![Molecular Crystal Diagram]
TYPES OF CRYSTALS

Metallic Crystals
- Lattice points occupied by
- Held together by
- Soft to hard, low to high melting point
- Good conductors of heat and electricity

AMORPHOUS SOLIDS
- Lack regular 3-D arrangement

Crystalline quartz (SiO₂)
Non-crystalline quartz glass
PHASE CHANGES

- Transformations from one phase to another
- Physical changes (change in molecular order)
- E added or removed

Liquid <---> Vapor

- Evaporation and Condensation
- E flow?
- Equilibrium Vapor Pressure (dynamic)
  - Measurable after dynamic equilibrium is established
Liquid <-> Vapor

Strength of IF indicated by $\Delta H_{vap}$
- $E$ required to vaporize 1 mole of a liquid
- Strong IF --->
- Clausius-Clapeyron Eqn (relates $P$ & $T$)

$$\ln P = \frac{-\Delta H_{vap}}{RT} + C$$
Liquid $\rightleftharpoons$ Vapor

\[
\ln P_1 = -\frac{\Delta H_{\text{vap}}}{RT_1} + C
\]

\[
\ln P_2 = -\frac{\Delta H_{\text{vap}}}{RT_2} + C
\]

\[\text{Liquid} \rightleftharpoons \text{Vapor}\]

- BP: Temperature at which the vapor pressure of a liquid = external pressure
- Relate BP to $\Delta H_{\text{vap}}$

<table>
<thead>
<tr>
<th>Substance</th>
<th>Boiling Point ($^\circ$C)</th>
<th>$\Delta H_{\text{vap}}$ (kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar</td>
<td>-186</td>
<td>6.3</td>
</tr>
<tr>
<td>Benzene (C₆H₆)</td>
<td>80.1</td>
<td>31.0</td>
</tr>
<tr>
<td>Ethanol (C₂H₅OH)</td>
<td>78.3</td>
<td>39.3</td>
</tr>
<tr>
<td>Diethyl ether (C₆H₁₄O₂)</td>
<td>64.6</td>
<td>28.0</td>
</tr>
<tr>
<td>Mercury (Hg)</td>
<td>357</td>
<td>59.0</td>
</tr>
<tr>
<td>Methane (CH₄)</td>
<td>-164</td>
<td>9.2</td>
</tr>
<tr>
<td>Water (H₂O)</td>
<td>100</td>
<td>40.7</td>
</tr>
</tbody>
</table>

Liquid $\rightleftharpoons$ Solid

- Freezing and melting (fusion)
- FP: T where melts (or freezes) at 1 atm
- E flow?
- Strength of IF indicated by $\Delta H_{\text{fus}}$
  - E required to melt 1 mole of a solid
Heating/Cooling Curves

- Equilibrium Temps
- Compare AB and CD
- Steepness of s, l, v lines?
- Supercooling

Solid <---> Vapor

- Sublimation and Deposition
- Solids have very low VP
- E to sublime 1 mole of a solid, $\Delta H_{sub}$
- Hess’s Law: $\Delta H_{sub} =$

PHASE DIAGRAMS

- The P & T conditions at which a substance exists as a solid, liquid, or gas
- Pure phases
- Boundary lines
- Triple point
- Predict changes in MP and BP
PHASE DIAGRAMS

Water

Pressure

Solid Liquid Vapor

1 atm

0.006 atm

0°C 100°C Temperature

Decreased melting point Increased boiling point

PHASE DIAGRAMS

CO₂

Pressure

Solid Liquid Vapor

5.2 atm

1 atm

-78°C -57°C Temperature

HOMEWORK

- 7-20
- 31, 32
- 41, 44
- 51-53, 55 (a, c-e, g, h)
- 77, 78, 84-86
- 91, 92, 94