CHEM1611 Worksheet 4: Intermolecular Forces and Introduction to Acids and Bases

Information

Intermolecular forces are the interactions between rather than inside molecules. They are responsible for many of the physical properties of substances, including their melting and boiling points.

In pure substances, there are 3 important intermolecular forces which may be present:

- **Dipole – dipole forces.** The dipole moment in a molecule will tend to align with those in its neighbours. This type of interaction is only possible if the molecule possesses a dipole.

- **Hydrogen bonds.** This is a particularly strong dipole – dipole interaction involving the interaction between the δ⁺ H atoms in very polar bonds and lone pairs on very electronegative atoms. Hydrogen bonding therefore requires the presence of both δ⁺ H atoms and electronegative atoms.

- **Dispersion forces.** These forces are present in all substances. At any moment in time, the electron density in a molecule or atom may not be symmetrical and this leads to a dipole moment. This momentary or instantaneous dipole moment induces matching dipoles in neighbouring molecules or atoms by polarizing their electron density.

  Dispersion forces increase with the number of electrons in a molecule or atom.

Model 1: Boiling Points Change Down a Group of the Periodic Table

Molecules are held in the liquid phase due to intermolecular forces so that boiling points are a good guide to their strength.

The figure opposite shows the boiling points of the Group 14 hydrides. All have the same shape but differ in the total number of electrons.

For example:

- C has 6 electrons and each H has 1 electron so CH₄ has 6 + 4 × 1 = 10.

- Sn has 50 electrons so SnH₄ has 54 electrons.

Critical thinking questions

1. What happens to the boiling point as the number of electrons increases?

2. What shape are the Group 14 hydrides?

3. Are dipole – dipole forces present in these molecules?

4. Is hydrogen bonding possible in these molecules?

5. What intermolecular force is present in these molecules?

6. Explain why the boiling points vary in the way you described in answer to Q1.
Model 2: Boiling Points Change Across a Row of the Periodic Table

On the graph opposite, the boiling points for the other hydrides have been added:

- Group 14 SiH₄, GeH₄ and SnH₄
- Group 15 PH₃, AsH₃ and SbH₃
- Group 16 H₂S, H₂Se and H₂Te
- Group 17 HCl, HBr and HI

Critical thinking questions

1. Use a Periodic Table to confirm that SiH₄, PH₃, H₂S and HCl all have 18 electrons.

2. What happens to the boiling point as the number of electrons increases? Why?

3. What are the molecular shapes of PH₃, H₂S and HCl?

4. Do PH₃, H₂S and HCl have dipole moments?

5. Why is the boiling point of SiH₄ lower than that of PH₃, H₂S and HCl?

6. Is the boiling point of SnH₄ (54 electrons) higher or lower than the boiling point of PH₃ (18 electrons)?

7. Explain your answer to Q6, making sure that it is consistent with your answers to Q2 and Q5.

Model 3: Anomalous Boiling Points of NH₃, H₂O and HF

The graph opposite adds the boiling points of CH₄, NH₃, H₂O and HF to Model 2. N, O and F are very electronegative and N-H, O-H and H-F bonds are very polar.

Critical thinking questions

1. How do the boiling points of the Group 14 hydrides change down the group?

Re-read your answers to Model 1.
2. How many $\delta^+$ H atoms are there on the most electronegative element in the molecules below?
(a) NH$_3$  (b) H$_2$O  (c) HF

3. How many lone pairs are there on the most electronegative element in these molecules?
(a) NH$_3$  (b) H$_2$O  (c) HF

4. Explain why the boiling points of NH$_3$, H$_2$O and HF (10 electrons) are higher than those of PH$_3$, H$_2$S and HCl (18 electrons). Refer to the Information if you are unsure.

5. Given your answer to Q4, suggest why the boiling point of NH$_3$ (10 electrons) is lower than that of SbH$_3$ (54 electrons).


7. Predict the relative strength of the intermolecular forces between two NH$_3$ molecules, two H$_2$O and two HF molecules.

8. How many hydrogen bonds can each NH$_3$ molecule make on average in NH$_3$(l)? (Hint: re-read your answers to Q2 and Q3).

9. How many hydrogen bonds can each HF molecule make on average in HF(l)? (Hint: re-read your answers to Q2 and Q3).

10. How many hydrogen bonds can each H$_2$O molecule make on average in H$_2$O(l)? (Hint: re-read your answers to Q2 and Q3).

11. Use your answers to Q6 – Q10 to explain why the boiling points vary in the order NH$_3$ < HF < H$_2$O.

Model 4: pH

Water is able to act as both an acid and a base and it is possible for water to react with itself in an acid-base reaction called the autoprotolysis or autoionization of water:

$$H_2O(l) + H_2O(l) \rightleftharpoons H_3O^+(aq) + OH^-(aq)$$

The equilibrium constant for this reaction $K_w = [H_3O^+(aq)][OH^-(aq)]$. At 25 °C, $K_w = 1.0 \times 10^{-14}$. Several definitions have proven to be useful:

$$\text{pH} = -\log_{10}[H_3O^+(aq)], \quad \text{pOH} = -\log_{10}[OH^-(aq)] \quad \text{p}K_w = -\log_{10}K_w$$
Critical thinking questions

1. During the course of a titration, a student measures the pH several times. What is $[\text{H}_3\text{O}^+(\text{aq})]$ for each pH value below? (Actually calculate $[\text{H}_3\text{O}^+(\text{aq})]$ – do not leave in the form $10^x$).

<table>
<thead>
<tr>
<th>pH</th>
<th>0.50</th>
<th>1.50</th>
<th>2.50</th>
<th>3.50</th>
<th>4.50</th>
<th>5.50</th>
<th>5.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[\text{H}_3\text{O}^+(\text{aq})]$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. What is the effect of the number to the left and to the right of the decimal point in the pH on $[\text{H}_3\text{O}^+(\text{aq})]$?

Model 5: Strong and Weak Acids

A strong acid is one that is essentially 100% dissociated in water: if 1.0 mole of the acid is added to enough water to make a 1.0 L solution, the solution will have $[\text{H}_3\text{O}^+(\text{aq})] = 1.0 \text{ M}$ and will be pH = 0.00.

A weak acid is one that is significantly less than 100% dissociated in water: if 1.0 mole of the acid is added to enough water to make a 1.0 L solution, the solution will have $[\text{H}_3\text{O}^+(\text{aq})] < 1.0 \text{ M}$ and will be pH > 0.

When an acid HA is placed in water, $\text{H}_3\text{O}^+(\text{aq})$ ions are produced according to the reaction below. The extent to which the reaction goes is given by the acid dissociation constant, $K_a$. The stronger the acid, the larger the value of $K_a$.

$$\text{HA(aq)} + \text{H}_2\text{O(l)} \rightleftharpoons \text{H}_3\text{O}^+(\text{aq}) + \text{A}^-(\text{aq})$$

$$K_a = \frac{[\text{H}_3\text{O}^+(\text{aq})][\text{A}^-(\text{aq})]}{[\text{HA(aq)}]}$$

Critical thinking questions

1. What are the major species present in a solution of a strong acid like HCl?

2. What are the major species present in a solution of a weak acid like CH₃COOH?

3. Under what pH conditions would CH₃COO⁻(aq) be the dominant species in a solution of CH₃COOH?

4. What are the major species present in a solution of a weak base like CH₃NH₂?

5. Under what pH conditions would CH₃NH₃⁺(aq) be the dominant species?

7. The extent of ionization of a drug helps determine how it is distributed in the body because ions are less likely to cross cell membranes than uncharged molecules. Are the two drugs below likely to be absorbed in (i) the acid environment of the stomach or (ii) the basic environment of the intestine?

![Aspirin](image1.png)

![Amphetamine](image2.png)