3 Chemical Bonding Tutorial

1 When magnesium is burnt in air, a mixture of the ionic solids –magnesium oxide, MgO, and magnesium nitride, Mg$_3$N$_2$, is formed.

(a) Use a dot-and-cross diagram to describe the bonding in Mg$_3$N$_2$.

**Ionic bonding**

\[
3\text{[Mg]^{2+}} \quad 2\text{[N$_3^-$]}^{3-}
\]

(b) State the factors that affect the magnitude of the lattice energy of an ionic compound.

Lattice energy depends on the **charges on the ions** and the **sizes of the ions**.

(c) How would you expect the magnitudes of the lattice energies of the oxides of the Group II elements to vary down the group?

**Down the group, the ionic radii of the Group II cations increase. As such, the magnitude of the lattice energies decreases down the group.**

(d) Suggest how the magnitude of the lattice energy of Mg$_3$N$_2$ might compare to that of MgO. Explain your answer.

The magnitude of the lattice energy of Mg$_3$N$_2$ is larger than that of MgO because N$^{3-}$ has a larger charge than O$^{2-}$.

[Note – effects of charges are more significant]

**Note: Examiners Report**

Candidates were clearly familiar with the factors influencing lattice enthalpies, and scored well on this part. If a mark was lost, it was often due to the use of the word “atom” rather than “ion” when referring to charges or sizes. The charge density of an ion *per se* is irrelevant to any discussion of lattice energy. Quite a number of candidates demonstrated an excellent grasp of the relative arguments, pointing out that the anionic size (N$^{3-}$ > O$^{2-}$) would suggest that the oxide would have the larger lattice energy, whereas the anionic charge (N$^{3-}$ > O$^{2-}$) would suggest the opposite. The anionic charge is the more important factor, making the lattice energy of the nitride larger than that of the oxide.

*N2008/ III/ 4d,e (modified)*
2 (a) Explain what is meant by sigma (σ) and pi (π) bonds. Illustrate your answers with suitable diagrams.

**Sigma bonds are formed by the ‘head-on’ overlap of two orbitals.**

![Diagram of sigma bond formation](image)

**Pi bonds are formed by the ‘side-on’ overlap of two orbitals.**

![Diagram of pi bond formation](image)

(b) How many sigma (σ) and pi (π) bonds are present in the propene (C₃H₆) molecule?

![Propene molecule](image)

8 sigma bonds and 1 pi bond.

(c) State the hybridization state of all the carbon atoms in the propene molecule.

![Propene molecule with hybridization](image)

sp³ sp² sp²

3 (a) State the VSEPR theory.

The VSEPR theory states that the shape of a molecule is determined by the extent of the repulsions between electron pairs.

1. Electron groups around a central atom locate themselves as far away from each other as possible to minimise electronic repulsion.

2. The extent of repulsions are as follows:
   Lone Pair–Lone Pair > Lone Pair–Bond Pair > Bond Pair–Bond Pair
(b) For each of the following molecules or ions below,
- draw their dot-and-cross diagrams to show the electronic structure;
- predict their shapes and state their bond angles;
- draw their structures showing their shapes.

<p>| | | | | | | |</p>
<table>
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<tbody>
<tr>
<td>(i)</td>
<td>O₂</td>
<td>(ii)</td>
<td>CO</td>
<td>(iii)</td>
<td>H₃O⁺</td>
<td>(iv)</td>
</tr>
<tr>
<td>(vi)</td>
<td>ICl₄⁻</td>
<td>(vii)</td>
<td>H₂O₂</td>
<td>(viii)</td>
<td>N₂H₄</td>
<td>(ix)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Dot-and-cross diagram</th>
<th>Shape and bond angle(s)</th>
<th>Structure showing shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) O₂</td>
<td><img src="image1" alt="Dot-and-cross diagram" /></td>
<td>linear</td>
<td><img src="image2" alt="Structure showing shape" /></td>
</tr>
<tr>
<td>(ii) CO</td>
<td><img src="image3" alt="Dot-and-cross diagram" /></td>
<td>linear</td>
<td><img src="image4" alt="Structure showing shape" /></td>
</tr>
<tr>
<td>(iii) H₃O⁺</td>
<td><img src="image5" alt="Dot-and-cross diagram" /></td>
<td>trigonal pyramidal, 107°</td>
<td><img src="image6" alt="Structure showing shape" /></td>
</tr>
<tr>
<td>(iv) BH₄⁻</td>
<td><img src="image7" alt="Dot-and-cross diagram" /></td>
<td>tetrahedral, 109.5°</td>
<td><img src="image8" alt="Structure showing shape" /></td>
</tr>
<tr>
<td>(v) SCl₂</td>
<td><img src="image9" alt="Dot-and-cross diagram" /></td>
<td>bent, 104.5°</td>
<td><img src="image10" alt="Structure showing shape" /></td>
</tr>
<tr>
<td>(vi) ICl₄⁻</td>
<td><img src="image11" alt="Dot-and-cross diagram" /></td>
<td>Square Planar, 90°</td>
<td><img src="image12" alt="Structure showing shape" /></td>
</tr>
</tbody>
</table>
4 Draw the structures for the following nitrogen oxides.

(a) NO  (b) NO₂  (c) N₂O  (d) N₂O₄  (e) N₂O₅

<table>
<thead>
<tr>
<th>NO</th>
<th>NO₂</th>
<th>N₂O</th>
<th>N₂O₄</th>
<th>N₂O₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>:N = O :</td>
<td>O=N=O</td>
<td>N=N=N=O</td>
<td>N=N=N=O</td>
<td>N=N=N=O</td>
</tr>
</tbody>
</table>
It is known that $\text{AlCl}_3$ and $\text{N(CH}_3\text{)}_3$ react readily.

(a) Draw the dot-and-cross diagram of the product of this reaction. Predict the likely shape of the product.

![Diag1](image1)

Tetrahedral about Al, N and C atoms.

(b) Explain why these two molecules form a product when they react in a molar ratio of 1:1.

$\text{AlCl}_3$ is electron-deficient as Al has only 6 electrons after sharing, and it can accept 2 more electrons.

$\text{N(CH}_3\text{)}_3$ contains a lone pair which can be donated to the electron deficient Al. Thus $\text{AlCl}_3$ and $\text{N(CH}_3\text{)}_3$ will react readily in a 1:1 ratio, forming a dative bond.

(c) Similar products may be obtained when the following compounds are reacted together. Suggest the structures and shapes of their products.

(i) $\text{BeCl}_2$ and $\text{NH}_3$

(ii) $\text{BF}_3$ and $\text{NaF}$

(b)(i)

![Diag2](image2)

Tetrahedral about N and Be atoms

(ii)

![Diag3](image3)

Tetrahedral about B atom
6 Antimony, Sb, is in Group V of the periodic Table. It forms a series of salts which contains the \( \text{SbF}_5^{n-} \) anion, the structure of which is a square-based pyramid:

![Square-based pyramid](image)

Deduce the total number of electrons around the antimony atom, the value of \( n \) and the oxidation number of Sb in this ion.

\[
\begin{align*}
\text{Total number of electrons around antimony} & = 12 \\
\text{(b)} & = 2 \\
\text{Oxidation number of Sb} & = +3
\end{align*}
\]

7 Account for the bond angles of the following species.

(a) | species | CH\(_4\) | NH\(_3\) | H\(_2\)O |
<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>bond angle/°</td>
<td>109.5</td>
<td>107</td>
<td>104.5</td>
</tr>
</tbody>
</table>

All 3 species have 4 electron pairs around the central atom which are arranged in a tetrahedral shape with a bond angle of 109.5°. According to the VSEPR theory, lone pair–lone pair repulsion > lone pair–bond pair > bond pair–bond pair.

As such, H\(_2\)O which has two lone pairs will experience the most electronic repulsion and thus has the smallest bond angle. CH\(_4\) which has only bond pairs will experience the least electronic repulsion and thus has the biggest bond angle.

(b) | species | NF\(_3\) | NH\(_3\) | BF\(_3\) |
<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>bond angle/°</td>
<td>102</td>
<td>107</td>
<td>120</td>
</tr>
</tbody>
</table>

NF\(_3\) and NH\(_3\) have 3 bond pairs and 1 lone pair with a trigonal pyramidal shape and a bond angle of 107° while BF\(_3\) has 3 bond pairs with a trigonal planar shape with a bond angle of 120°. As such, NF\(_3\) and NH\(_3\) have a smaller bond angle than BF\(_3\).

F is more electronegative than H.

As such, the bond pairs in NF\(_3\) are further away from the central N atom, which decreases the repulsion between bond pairs and decrease the bond angle.

The bond pairs in NH\(_3\) are closer to N, thus occupying a larger volume around the N atom and hence increases in bond pair-bond pair repulsion, which increases bond angle.
8 The table below gives the solubility* of a series of alcohols in water and hexane.

<table>
<thead>
<tr>
<th>alcohol</th>
<th>solubility in water</th>
<th>solubility in hexane (C₆H₁₄)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₃OH</td>
<td>∞</td>
<td>1.2</td>
</tr>
<tr>
<td>CH₃CH₂OH</td>
<td>∞</td>
<td>∞</td>
</tr>
<tr>
<td>CH₃CH₂CH₂OH</td>
<td>∞</td>
<td>∞</td>
</tr>
<tr>
<td>CH₃CH₂CH₂CH₂OH</td>
<td>1.1</td>
<td>∞</td>
</tr>
<tr>
<td>CH₃CH₂CH₂CH₂CH₂OH</td>
<td>0.30</td>
<td>∞</td>
</tr>
</tbody>
</table>

*Solubility is expressed in mol alcohol/ 1000 g solvent at 20°C

(a) Draw a diagram to show how hydrogen bonding occurs between CH₃OH and water.

(b) State the solubility trends of the alcohols in water and in hexane and account for them.

As the length of the alkyl chain increases, the solubility of alcohol in water decreases and the solubility in hexane increases.

**Solubility in water**
All alcohols can form strong intermolecular hydrogen bonding with water molecules via the O-H group.

For alcohols with short alkyl chains, the energy released from the solute-solvent interaction (hydrogen bonding) is greater than the energy required to break the solute-solute interaction (dispersion forces and hydrogen bonding) and the solvent-solvent interactions (hydrogen bonding).

As the length of the non-polar alkyl chains increases, the dispersion forces between alcohol molecules also increases and become a predominant force. The energy released from the solute-solvent interaction (hydrogen bonding) is insufficient to overcome the increasing strength of the dispersion forces between alcohol molecules.
(Note: the long R chain also interferes with the hydrogen bond formation between water and the alcohol.)

**Solubility in hexane**
All alcohols will interact with non-polar hexane molecules through dispersion forces via their non-polar alkyl chain.

Since the solute-solvent interaction (dispersion forces) is comparable in strength to the solute-solute interactions, all alcohols are soluble in hexane. The increase in solubility in hexane is due to the increase in length of the non-polar alkyl group which is able to form stronger dispersion forces with hexane molecules.
Self-practice Questions

GCE A-level Chemistry Paper

1  N12  P1  Q5
2  N12  P1  Q31
3  N12  P3  Q1  (b)(i)(ii)
4  N11  P3  Q1  (a)(b)
5  N10  P1  Q32
6  N10  P1  Q4
7  N10  P1  Q5
8  N10  P1  Q6
9  N10  P3  Q4  (c)
10 N09  P1  Q19
11 N09  P1  Q35
12 N09  P1  Q5
13 N09  P1  Q6
14 N09  P1  Q32
15 N09  P2  Q1  (d)(e)
16 N09  P3  Q4  (b)(i), (ii)
17 N08  P1  Q3
18 N08  P1  Q6
19 N08  P1  Q8
20 N08  P1  Q19
21 N08  P1  Q31
22 N07  P1  Q6
23 N07  P1  Q7
24 N07  P1  Q18
25 N07  P1  Q31
26 N07  P2  Q4  (c)
27 N06  P1  Q4
28 N06  P1  Q5
29 N06  P1  Q12
30 N06  P1  Q32
31 N06  P2  Q1  (a)
32 N06  P3  Q2  (a)
33 N05  P1  Q5
34 N05  P1  Q6
35 N05  P1  Q31
36 N05  P1  Q34
37 N04  P1  Q3
38 N04  P1  Q5
39 N04  P3  Q1  (d)
40 N03  P1  Q6
41 N03  P1  Q13
42 N03  P1  Q15
43 N03  P3  Q1  (a), (b)

Answers to Self-practice Questions

1  C
2  A
3  (i)
   
   (ii) Trigonal Planar
4  (a)  \[ x + (-4) = -1 \]
\[ x = +3 \]
Therefore, oxidation number of iodine in \( \text{ICl}_4^- \) is +3.

(b)  Applying VSEPR theory, as lone pair – lone pair repulsion > lone pair – bond pair repulsion > bond pair – bond pair repulsion, their shapes are as follows:

![Chemical Bonding Diagram](attachment:image.png)

5  B
6  D
7  B
8  C

9  (i)  Bond angle of \( \text{O}_3 \) is 115° since there are 2 bond pairs and 1 lone pair around the central O atom and bond pair – bond pair repulsion is weaker than lone pair – bond pair repulsion.

Bond angle of \( \text{NO}_2 \) is 118° since there are 2 bond pairs and 1 lone electron around the central N atom. Since the repulsion between the bond pair and the lone electron is less than the repulsion between the bond pair and lone pair in \( \text{O}_3 \), bond angle is larger than in \( \text{O}_3 \).

(ii)  \( \text{Cl} \) can expand octet due to available vacant 3d orbitals to accept electrons in forming covalent bonds with O.

F cannot expand octet and is unable to form 2 dative bonds due to its high electronegativity.

10  B  11  D
15 (i) Coordination number refers to the number of oppositely-charged ions that are adjacent to a particular ion in the crystal lattice.

(ii) Cs\(^+\) cation is larger than Na\(^+\) and K\(^+\). Thus, the Cs\(^+\) ion can be surrounded by more Cl\(^-\) anions.

16 (i) \(\text{NH}_3\) experiences intermolecular hydrogen bonding while \(\text{CH}_4\) only has intermolecular dispersion forces. As hydrogen bonding is stronger, more energy is required to boil \(\text{NH}_3\) than \(\text{CH}_4\).

(ii) N.A. Not Chemical Bonding question

26 (i) \[
\begin{array}{c}
\text{Cl}_3 \\
\text{C} \\
\text{Cl}_2
\end{array}
\]

(ii) 120°

31 \[
[\text{Ca}]^{2+} \cdot 2[\text{F}_2^-]
\]

32 Based on VSEPR theory, electron pairs around central atom are arranged as far apart as possible to minimize electronic repulsion. 3 bond pair and no lone pair around B \(\Rightarrow\) Shape is trigonal planar

33 A
34 A
35 A
(i) There are two covalent double bonds between C & 2 O atoms. It has a linear shape.

(ii) Square planar

(b) temporary dipole-induced dipole interactions (between gaseous molecules) and permanent dipole - permanent dipole interactions between molecules in solid state as CO₂ has polar C=O bonds