

Inorganic Chemistry with Doc M. Group: \_\_\_\_\_

Names: \_\_\_\_\_

### Day 4. Intermolecular forces.

#### A. Covalent forces

|     |                                 |
|-----|---------------------------------|
| C-C | $\Delta H = 347 \text{ kJ/mol}$ |
| H-H | $\Delta H = 431 \text{ kJ/mol}$ |
| F-F | $\Delta H = 155 \text{ kJ/mol}$ |

#### B. Ionic forces ( $E = Z^+Z^-/r$ )

|  |   |
|--|---|
| LiF $\longrightarrow$ Li <sup>+</sup> (g) + F <sup>-</sup> (g) | $\Delta H = 755 \text{ kJ/mol}$ (reverse of lattice energy) |
| LiF $\longrightarrow$ Li(g) + F(g)                             | $\Delta H = 567 \text{ kJ/mol}$                             |

#### C. Metallic forces (metal cations in a “sea of electrons”: M(s) $\rightarrow$ M(g))

|    |  |
|----|--|
| Fe | $\Delta H = 416 \text{ kJ/mol}$                            |
| W  | $\Delta H = 849 \text{ kJ/mol}$                            |
| Pb | $\Delta H = 195 \text{ kJ/mol}$                            |
| Hg | $\Delta H = 61 \text{ kJ/mol}$ (Hg(l) $\rightarrow$ Hg(g)) |

#### D. Network covalent forces (endless lattice of covalent bonds)

|    |   |
|----|---|
| C  | $\Delta H = 717 \text{ kJ/mol}$ (C(s) $\rightarrow$ C(g))   |
| Si | $\Delta H = 450 \text{ kJ/mol}$ (Si(s) $\rightarrow$ Si(g)) |

#### E. Intermolecular forces

##### 1. Dipole-dipole forces (3 – 4 kJ/mol)

For the polar molecule: the dipole forces is given by  $\mu = qr$  where  $q$  = the equal and opposite charges in the molecule ( $\delta^+$ ,  $\delta^-$ ) and  $r$  is the distance between  $\delta^+$  and  $\delta^-$ .

For dipole-dipole forces,  $E \propto \frac{-\mu_A \mu_B}{r^3}$

| Molecule        | Dipole? | MM (g/mol) | bp (K) |
|-----------------|---------|------------|--------|
| F <sub>2</sub>  |         | 38         | 85     |
| Cl <sub>2</sub> |         | 71         |        |
| ClF             |         | 55         |        |

2. Hydrogen bonding forces (10 - 40 kJ/mol)

- Extra-effective dipole-dipole force that occurs when N-H, O-H and F-H bonds exist.
- For neutral molecules, oxygen has the optimal balance between bonding groups (potentially hydrogen atoms and electron pair groups; both are required for hydrogen bonding):

| Atom | B groups | E-groups | Example          |
|------|----------|----------|------------------|
| N    |          |          | NH <sub>3</sub>  |
| O    |          |          | H <sub>2</sub> O |
| F    |          |          | HF               |

c. Boiling points of Groups IV, V, VI, and VII hydrides:

| Molecule         | MM (g/mol) | bp (°C) | state at 25 °C |
|------------------|------------|---------|----------------|
| CH <sub>4</sub>  | 16         | -164    | gas            |
| SiH <sub>4</sub> | 32         |         |                |
| GeH <sub>4</sub> | 77         |         |                |

| Molecule         | MM (g/mol) | bp (°C) | state at 25 °C |
|------------------|------------|---------|----------------|
| NH <sub>3</sub>  | 17         | -33     | gas            |
| PH <sub>3</sub>  | 34         |         |                |
| AsH <sub>3</sub> | 78         |         |                |
| SbH <sub>3</sub> | 125        |         |                |
| BiH <sub>3</sub> | 212        |         |                |

| Molecule         | MM (g/mol) | bp (°C) | state at 25 °C |
|------------------|------------|---------|----------------|
| OH <sub>2</sub>  | 18         |         |                |
| SH <sub>2</sub>  | 34         |         | gas            |
| SeH <sub>2</sub> | 81         |         | gas            |
| TeH <sub>2</sub> | 130        | -2      | gas            |

| Molecule | MM (g/mol) | bp (°C) | state at 25 °C |
|----------|------------|---------|----------------|
| FH       | 20         | +20     | gas            |
| ClH      | 36         |         |                |
| BrH      | 81         |         |                |

d. Hydrogen bonding occurs in solutions even when only one of the members can actually hydrogen bond. For example, aqueous methanal (formaldehyde, HCHO): the aldehyde has no hydrogen-bonding H, but it has two lone pairs on oxygen that can participate in H-bonding with water's O-H hydrogens.

3. Instantaneous dipole (London-dispersion) forces (1 – 10 kJ/mol)

A. Strength of the forces:  $E \propto \frac{-IE\alpha^2}{r^6}$  where  $\alpha$  is the polarizability and IE is the ionization energy

1. The polarizability increases with MM and shape of the molecule

MM factors: All molecules have MM so all molecules have LDF to some extent.

| Molecule        | MM (g/mol) | bp (K) | state at 25 °C |
|-----------------|------------|--------|----------------|
| F <sub>2</sub>  | 38         |        |                |
| Cl <sub>2</sub> | 71         |        |                |
| Br <sub>2</sub> | 160        |        |                |
| I <sub>2</sub>  | 254        |        |                |

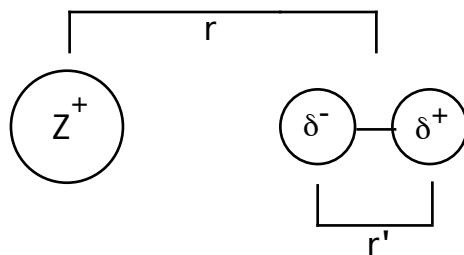
| Molecule                           | MM (g/mol) | bp (°C) | state at 25 °C |
|------------------------------------|------------|---------|----------------|
| n-C <sub>5</sub> H <sub>12</sub>   | 72         |         |                |
| iso-C <sub>5</sub> H <sub>12</sub> | 72         |         |                |
| neo-C <sub>5</sub> H <sub>12</sub> | 72         |         |                |

4. Ion-dipole forces (10 – 50 kJ/mol)

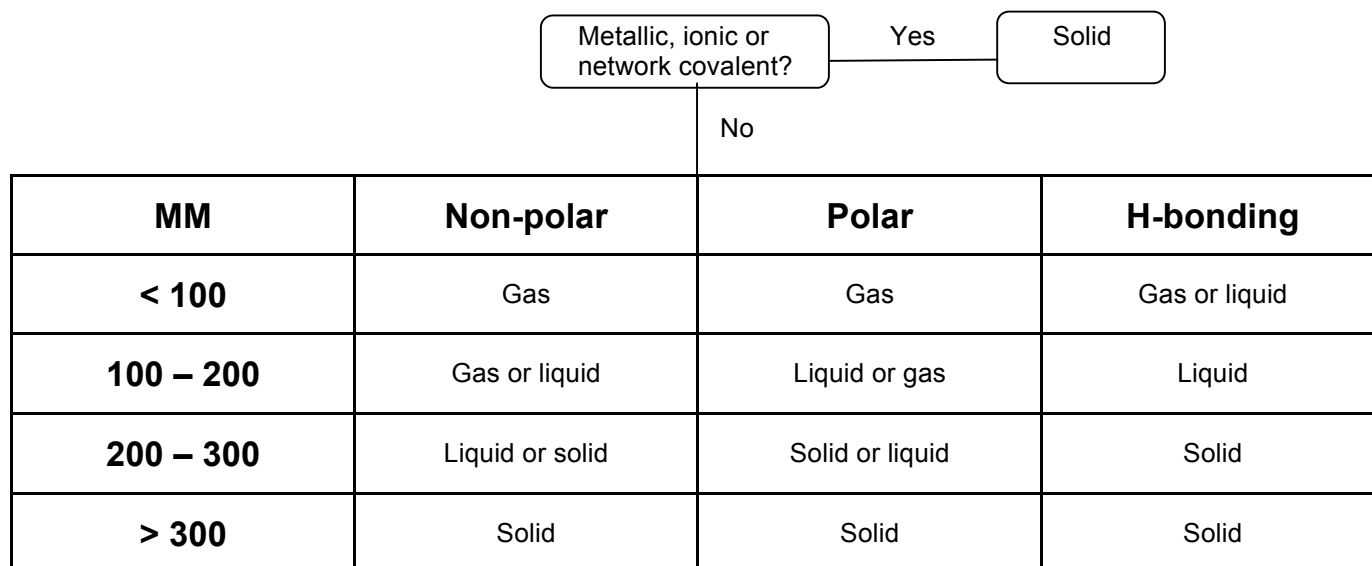
Only applies to solutions, usually aqueous solutions

For polar molecule: the dipole force is given by  $\mu = qr$  where  $q$  = the equal and opposite charges in the molecule ( $\delta^+$ ,  $\delta^-$ ) and  $r$  is the distance between  $\delta^+$  and  $\delta^-$  and  $e$  is the charge on the ion.

For ion-dipole forces,  $E \propto \frac{\mu e}{r^2}$



C. Pulling it all together. This chart is overly simplistic, but it shows how LDF can be a very important factor (high MM). In the chart, the MM cut-offs of 100 and 200 g/mol, are rather arbitrary and you can expect to find numerous exceptions.



1. Use the chart to predict the physical state at room temperature for each of the following. Also, identify which forces led you to your conclusion. In our next class, I will “reveal” the actual melting and boiling points! (Or, if you just can’t wait, look them up in a chemistry handbook!)

| Compound:   | Actual mp, bp, phase at room temperature |
|---|--|
| AsBr <sub>3</sub><br>MM = 315 g/mol                             |  |
| BF <sub>3</sub><br>MM = 68 g/mol                                |  |
| CSe <sub>2</sub><br>MM = 170 g/mol                              |  |
| CH <sub>3</sub> Cl<br>MM = 50.5 g/mol                           |  |
| NH <sub>4</sub> Br<br>MM = 98 g/mol                             |  |
| CCl <sub>4</sub><br>MM = 154 g/mol                              |  |
| ClO <sub>2</sub><br>MM = 67.5 g/mol                             |  |
| ClF <sub>3</sub><br>MM = 92.5 g/mol                             |  |
| Cl <sub>2</sub> O <sub>7</sub><br>MM = 183 g/mol                |  |
| (C <sub>2</sub> F <sub>4</sub> ) <sub>n</sub><br>MM = 100 g/mol |  |
| PSCl <sub>3</sub><br>MM = 169.5 g/mol                           |  |
| PSBr <sub>3</sub><br>MM = 303 g/mol                             |  |

|  |  |
|--|--|
| $\text{SCl}_2\text{O}_2$<br>MM = 135 g/mol   |  |
| $\text{BaCl}_2$<br>MM = 208 g/mol  |  |
| $\text{GeBr}_4$<br>MM = 392 g/mol  |  |
| $\text{PBr}_3$<br>MM = 271 g/mol   |  |
| $\text{C}_2\text{H}_6\text{O}$ , ethanol, $\text{C}_2\text{H}_5\text{OH}$<br>MM = 46 g/mol |  |
| $\text{C}_2\text{H}_6\text{O}$ , dimethylether, $\text{CH}_3\text{OCH}_3$<br>MM = 46 g/mol |  |
| $\text{SiC}$<br>MM = 43 g/mol  |  |
| $\text{PF}_3$<br>MM = 88 g/mol   |  |
| $\text{PF}_5$<br>MM = 126 g/mol  |  |
| $\text{PCl}_3$<br>MM = 137.5 g/mol   |  |
| $\text{MgO}$<br>MM = 40.3 g/mol  |  |
| $\text{Fe}$<br>MM = 55.9 g/mol   |  |
| $(\text{C}_2\text{H}_5)_2\text{NH}$<br>MM = 73 g/mol                                       |  |
| $(\text{CH}_3)_2\text{NH}$<br>MM = 45 g/mol  |  |
| $(\text{CH}_3)_3\text{N}$<br>MM = 59 g/mol   |  |

**Inorganic Chemistry with Doc M.**  
**Fall Semester, 2009**

**Answers**

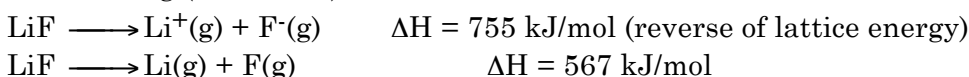
**Day 4. Intermolecular forces.**

A. Covalent and ionic forces

1. Covalent bonding

|     |            |
|-----|------------|
| C-C | 347 kJ/mol |
| H-H | 431 kJ/mol |
| F-F | 155 kJ/mol |

2. Ionic bonding ( $E = Z^+Z^-/r$ )



B. Intermolecular forces

1. Dipole-dipole forces (3 – 4 kJ/mol)

For the polar molecule: the dipole forces is given by  $\mu = qr$  where  $q$  = the equal and opposite charges in the molecule ( $\delta^+$ ,  $\delta^-$ ) and  $r$  is the distance between  $\delta^+$  and  $\delta^-$ .

For dipole-dipole forces,  $E = -2\mu_A \mu_B/r^3$

| Molecule        | Dipole? | MM (g/mol) | bp (K) |
|-----------------|---------|------------|--------|
| F <sub>2</sub>  | No      | 38         | 85     |
| Cl <sub>2</sub> | No      | 71         | 239    |
| ClF             | Yes     | 55         | 172    |

2. Hydrogen bonding forces (10 - 40 kJ/mol)

- Extra-effective dipole-dipole force that occurs when N-H, O-H and F-H bonds exist.
- For neutral molecules, oxygen has the optimal balance between bonding groups (potentially hydrogen atoms and electron pair groups; both are required for hydrogen bonding:

| Atom | B groups | E-groups | Example          |
|------|----------|----------|------------------|
| N    | 3        | 1        | NH <sub>3</sub>  |
| O    | 2        | 2        | H <sub>2</sub> O |
| F    | 1        | 3        | HF               |

c. Boiling points of Groups IV, V, VI, and VII hydrides:

| Molecule         | MM (g/mol) | bp (°C) | state at 25 °C |
|------------------|------------|---------|----------------|
| CH <sub>4</sub>  | 16         | -164    | gas            |
| SiH <sub>4</sub> | 32         | -112    | gas            |

|                  |    |     |     |
|------------------|----|-----|-----|
| GeH <sub>4</sub> | 77 | -89 | gas |
|------------------|----|-----|-----|

| Molecule         | MM (g/mol) | bp (°C) | state at 25 °C |
|------------------|------------|---------|----------------|
| NH <sub>3</sub>  | 17         | -33     | gas            |
| PH <sub>3</sub>  | 34         | -87     | gas            |
| AsH <sub>3</sub> | 78         | -55     | gas            |
| SbH <sub>3</sub> | 125        | -17     | gas            |
| BiH <sub>3</sub> | 212        | +22     | gas            |

| Molecule         | MM (g/mol) | bp (°C) | state at 25 °C |
|------------------|------------|---------|----------------|
| OH <sub>2</sub>  | 18         | +100    | liquid         |
| SH <sub>2</sub>  | 34         | -61     | gas            |
| SeH <sub>2</sub> | 81         | -42     | gas            |
| TeH <sub>2</sub> | 130        | -2      | gas            |

| Molecule | MM (g/mol) | bp (°C) | state at 25 °C |
|----------|------------|---------|----------------|
| FH       | 20         | +20     | gas            |
| ClH      | 36         | -85     | gas            |
| BrH      | 81         | -67     | gas            |

d. Hydrogen bonding occurs in solutions even when only one of the members can actually hydrogen bond (e.g. aqueous methanal (formaldehyde, HCHO))

### 3. Instantaneous dipole (London-dispersion) forces (1 – 10 kJ/mol)

A. Strength of the forces:  $E = -3I\alpha^2/4r^6$      $\alpha$  is the polarizability and  $I$  is the ionization energy

1. The polarizability increases with MM and shape of the molecule

MM factors: All molecules have MM so all molecules have LDF to some extent.

| Molecule        | MM (g/mol) | bp (K) | state at 25 °C |
|-----------------|------------|--------|----------------|
| F <sub>2</sub>  | 38         | 85     | gas            |
| Cl <sub>2</sub> | 71         | 239    | gas            |
| Br <sub>2</sub> | 160        | 332    | Liquid         |
| I <sub>2</sub>  | 254        | 458    | solid          |

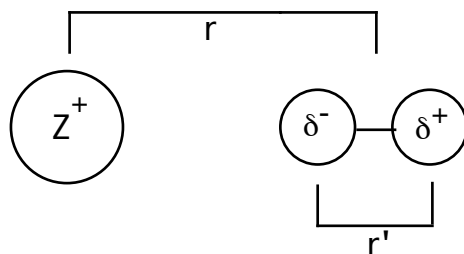
| Molecule                           | MM (g/mol) | bp (°C) | state at 25 °C |
|------------------------------------|------------|---------|----------------|
| n-C <sub>5</sub> H <sub>12</sub>   | 72         | 36.07   | liquid         |
| iso-C <sub>5</sub> H <sub>12</sub> | 72         | 27.85   | liquid         |
| neo-C <sub>5</sub> H <sub>12</sub> | 72         | 9.6     | gas            |

4. Ion-dipole forces (10 – 50 kJ/mol)

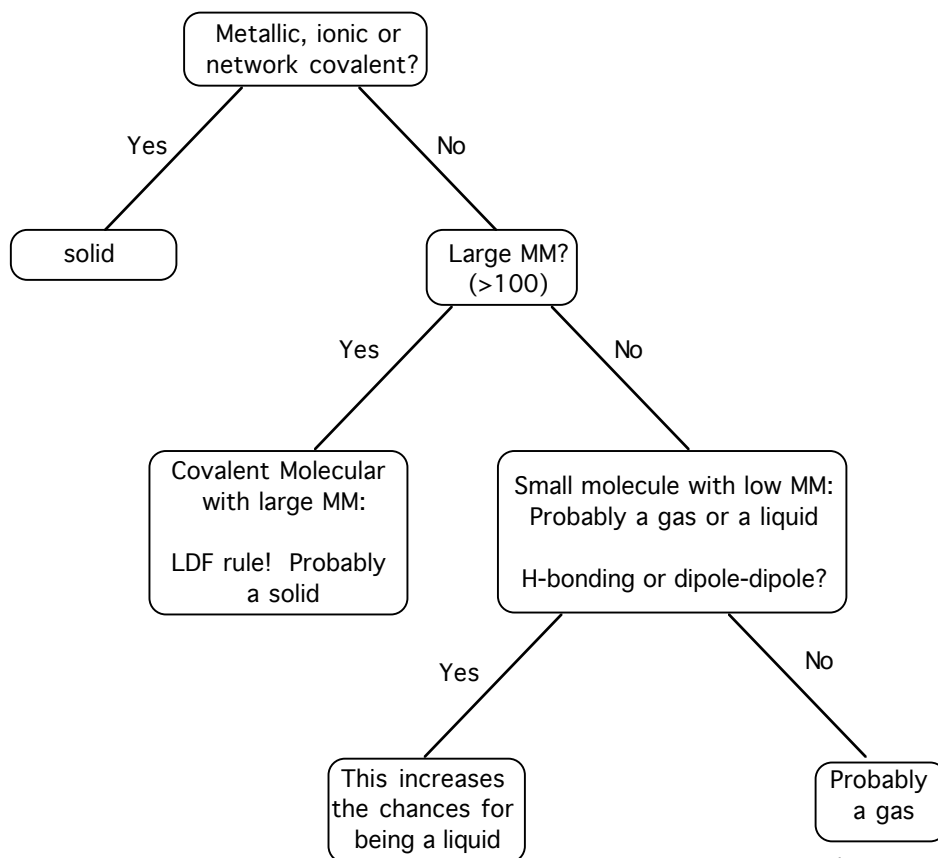
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For the polar molecule: the dipole forces is given by  $\mu = qr$  where  $q =$  the equal and opposite charges in the molecule ( $\delta^+$ ,  $\delta^-$ ) and  $r$  is the distance between  $\delta^+$  and  $\delta^-$ .

For ion-dipole forces,  $E = -|Z^\pm| \mu/r^2$



C. Pulling it all together. This chart is overly simplistic, but it shows how LDF can be the most important factor (high MM). In the chart, high MM is set at 100 g/mol, which is rather arbitrary.



1. Use the chart to predict the physical state at room temperature for each of the following. Also, identify which forces led you to your conclusion. Then, look up the mp and bp of these substances up in a chemistry handbook and see how you did! Indicate when the chart “failed” you.

|                                |
|--------------------------------|
| AsBr <sub>3</sub>              |
| BF <sub>3</sub>                |
| CSe <sub>2</sub>               |
| CH <sub>3</sub> Cl             |
| CCl <sub>4</sub>               |
| ClO <sub>2</sub>               |
| ClF <sub>3</sub>               |
| Cl <sub>2</sub> O <sub>7</sub> |

|  |
|--|
| GeBr <sub>4</sub>  |
| PBr <sub>3</sub>   |
| C <sub>2</sub> H <sub>6</sub> O, ethanol, C <sub>2</sub> H <sub>5</sub> OH       |
| C <sub>2</sub> H <sub>6</sub> O, dimethylether, CH <sub>3</sub> OCH <sub>3</sub> |
| SiC  |
| MgO  |
| Fe   |

## Review for ACS Final Exam in Inorganic Chemistry

### Intermolecular forces

1. Which of these compounds most likely a gas at room temperature?

- (a) BF<sub>3</sub>
- (b) PBr<sub>3</sub>
- (c) K<sub>2</sub>S<sub>2</sub>O<sub>3</sub>
- (d) SnF<sub>2</sub>
- (e) SiO<sub>2</sub>

2. Which of these compounds exhibits hydrogen bonding?

- (a) B<sub>2</sub>H<sub>6</sub>
- (b) CH<sub>4</sub>
- (c) CH<sub>3</sub>CH<sub>2</sub>NCl<sub>2</sub>
- (d) CH<sub>3</sub>OCl
- (e) HOBr

3. Lattice energy is greatest for:

- (a) NaCl
- (b) MgO
- (c) BaCl<sub>2</sub>
- (d) Na<sub>2</sub>O
- (e) CsF

4. Identify the species with the highest melting point.

- (a) AsCl<sub>3</sub>
- (b) NH<sub>4</sub>C<sub>2</sub>H<sub>3</sub>O<sub>2</sub>
- (c) SiC
- (d) Mn
- (e) S<sub>8</sub>

**Answers: A, E, B, C**