States of Matter and Energy

Kinetic Molecular Theory

- Matter is made of infinitesimal particles
- The particles are in constant random motion (kinetic energy)
- The particles interact through repulsions and attractions (potential energy)
- The average kinetic energy is proportional to the Kelvin temperature
- The particles transfer energy through elastic collisions (no energy is lost)

Definitions of states

- Solid
  - Potential energy is greater than the kinetic energy
  - Particles are close together and cannot move much
  - Compressibility is low and thermal expansion is low

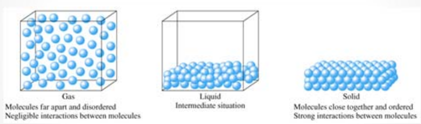
Definition of states

- Liquid
  - Potential energies and kinetic energies are about equal
  - Some room between particles and can move to an extent around one another
  - Compressibility is moderate and thermal expansion is a little higher than in solids

Definition of states

- Gas
  - Potential energies are much lower than kinetic energies
  - A lot of room between particles and can move freely
  - Compressibility is high and thermal expansion is higher than in solids or liquids

Definition of states



Energy

- Kinds of energy
  - Heat
  - Light
  - Chemical
  - Mechanical
  - Electrical
  - Sound
  - Etc.

Energy

- Let's look at the formula for kinetic energy

$$KE = \frac{1}{2}mv^2$$

Mass is in kg, velocity is in m s^{-1} so energy has units of kg m^2 s^{-2}

Enter the Joule

- kg m^2 s^{-2} is also called the ***Joule (J)*** and is the SI unit of energy
- Another energy unit you should know is the calorie (cal) which is defined as the amount of energy needed to increase the temperature of 1 g of water from 14.5°C to 15.5°C .
- 1 cal = 4.184 J

Specific heat

- Amount of energy needed to increase the temperature of 1 g of a substance by 1 °C.
- Has units of J g^{-1} $°C^{-1}$
- Definition is similar to that of the calorie and the specific heat of water is 1 cal g^{-1} $°C^{-1}$ or ***4.184 J g^{-1} $°C^{-1}$***

Energy calculations

$$q = ms\Delta T = ms\left(T_f - T_i\right)$$

q is heat (J), m is mass (g), s is specific heat (J g^{-1} $°C^{-1}$), T_f is the final temperature (°C) and T_i is the initial temperature.

If $q < 0$, heat exits the system and is called exothermic. If $q > 0$, heat enters the system and is called endothermic.

This is only valid if there is no phase change

How to determine specific heat.

- We need to remember three things.
  - When an object transfers heat, the amount of heat lost by the hot object is equal the amount of heat gained by the cold object.
  - Heat flows from the hot object to the cold object
  - The final temperature of both objects will be the same
- How do we use these facts?

Mathematical representation

$$q_h = -q_c$$

$$m_h s_h \Delta T_h = -m_c s_c \Delta T_c$$

$$m_h s_h \left(T_{f,h} - T_{i,h}\right) = -m_c s_c \left(T_{f,c} - T_{i,c}\right)$$

$$T_{f,h} = T_{f,c} = T_f$$

$$m_h s_h \left(T_f - T_{i,h}\right) = -m_c s_c \left(T_f - T_{i,c}\right)$$

Calculations

$$m_h s_h \left(T_f - T_{i,h}\right) = -m_c s_c \left(T_f - T_{i,c}\right)$$

Solve for specific heat of hot object

$$s_h = \frac{-m_c s_c \left(T_f - T_{i,c}\right)}{m_h \left(T_f - T_{i,h}\right)}$$

Example

- A 7.683 g piece of iron is heated to 67.3°C and placed in to 56.323 g of a liquid with an initial temperature of 25.6°C. The final temperature of both is 36.2°C. What is the specific heat of the liquid?
  - Method 1
  - Method 2

Solution

$$m_{Fe} s_{Fe} \Delta T_{Fe} = -m_l s_l \Delta T_l$$

$$(7.683\text{ g})\left(0.444\text{ J g}^{-1}\ {}^\circ\text{C}^{-1}\right)\left(36.2\ {}^\circ\text{C} - 67.3\ {}^\circ\text{C}\right) = -(56.323\text{ g})\, s_l \left(36.2\ {}^\circ\text{C} - 25.6\ {}^\circ\text{C}\right)$$

$$-106.0899\text{ J} = \left(-597.024\text{ g }{}^\circ\text{C}\right) s_l$$

$$s_l = \frac{-106.0899\text{ J}}{-597.024\text{ g }{}^\circ\text{C}} = 0.178\text{ J g}^{-1}\ {}^\circ\text{C}^{-1}$$

Solution

- Use equation to solve for specific heat: $s_c = \dfrac{-m_h s_h \left(T_f - T_{i,h}\right)}{m_c \left(T_f - T_{i,c}\right)}$

Plug in the numbers

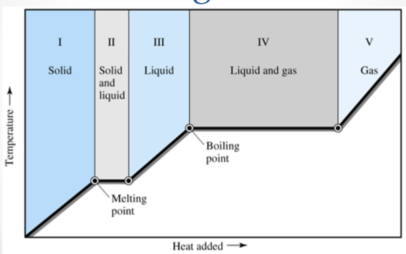
$$s_c = \frac{-(7.683\text{ g})\left(0.444\text{ J g}^{-1}\ {}^\circ\text{C}^{-1}\right)\left(36.2^\circ\text{C} - 67.3^\circ\text{C}\right)}{(56.323\text{ g})\left(36.2^\circ\text{C} - 25.6^\circ\text{C}\right)}$$

$$= 0.178\text{ J g}^{-1}\ {}^\circ\text{C}^{-1}$$

What about phase changes?

- What happens in a phase change?
  - Heat goes into increasing the kinetic energy of the particles, just like when we heat a substance without a phase change.
  - The increase of kinetic energy is not manifested as an increase in temperature though, it goes into moving the particles farther apart (reducing the potential energy).
  - ***There is no temperature change***

Heating curves



Heat during a phase change

- If there is no temperature change during a phase change, how do we calculate the amount of heat transferred?
  - By using the heat of phase change.
    - ΔH_{fus} for melting or freezing
    - ΔH_{vap} for boiling or condensing
    - ΔH_{sub} for sublimation or deposition

Heat of phase change

- Has units of J g^{-1} or J mol^{-1}
- Can be positive or negative
  - ΔH_{fus} is positive if we are melting (heat going into the solid to convert to liquid.
  - ΔH_{fus} is negative if we are freezing (heat coming out of liquid to convert to solid)

Example

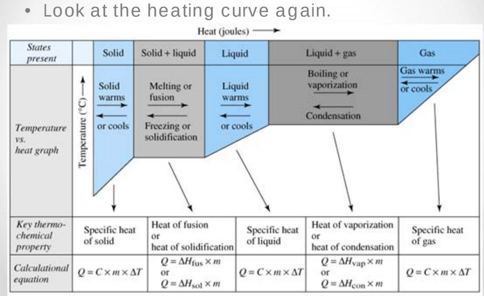
- How many joules of heat need to be removed from 150.0 g of liquid water at 0.0°C to convert it completely to ice at that temperature?

$$q = m\Delta H_{fus} = 150.0 \text{ g} \times \left(-334 \text{ J g}^{-1}\right)$$
$$= -5.01 \times 10^{4} \text{ J}$$

The negative sign indicates that heat was removed.

What about phase changes with temperature changes?

- Look at the heating curve again.



How many Joules of energy are needed to change 15.0 g of ice at -16.3°C to steam at 106.3°C?

Solution

- Calculate the energy to raise the temperature of ice from -16.3°C to 0.0°C.

$$q_1 = (15.0\ \text{g})(2.1\ \text{J g}^{-1}\ {}^\circ\text{C}^{-1})(0.0\ {}^\circ\text{C} - (-16.3\ {}^\circ\text{C}))$$
$$= 5\underline{1}3.45\ \text{J}$$

Solution

- Calculate the energy to melt the ice

$$q_2 = (15.0\ \text{g})(334\ \text{J g}^{-1})$$
$$= 50\underline{1}0\ \text{J}$$

Solution

- Calculate the energy to increase the temperature of the water from 0.0°C to 100.0°C.

$$q_3 = (15.0\ \text{g})(4.184\ \text{J g}^{-1}\ {}^\circ\text{C}^{-1})(100.0^\circ\text{C} - 0.0^\circ\text{C})$$
$$= 62\underline{7}6\ \text{J}$$

Solution

- Calculate the energy to boil the water

$$q_4 = (15.0\ \text{g})(2260\ \text{J g}^{-1})$$
$$= 33\underline{9}00\ \text{J}$$

Solution

- Calculate the energy to increase the temperature of the steam from 100.0°C to 106.3°C.

$$q_5 = (15.0\ \text{g})(2.0\ \text{J g}^{-1}\ {}^\circ\text{C}^{-1})(106.3^\circ\text{C} - 100.0^\circ\text{C})$$
$$= 18\underline{9}\ \text{J}$$

Solution

- Add the results of the previous calculations:

$$q_T = q_1 + q_2 + q_3 + q_4 + q_5$$
$$= 5\underline{1}3.45\ \text{J} + 50\underline{1}0\ \text{J} + 62\underline{7}6\ \text{J} + 33\underline{9}00\ \text{J} + 18\underline{9}\ \text{J}$$
$$= 45\underline{8}88.45\ \text{J} = 4.59 \times 10^4\ \text{J}$$

Potential Energy

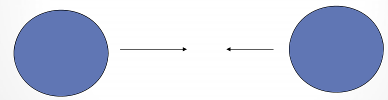
What causes molecules to stick together?

Attractive forces

- All molecules and atoms have attractive forces between them. Otherwise we wouldn't be able to liquefy or solidify anything.
- The attractive forces present depend on the kind of molecule and the molecule's shape.

Kinds of attractive forces

- London Forces
  - Exist between all molecules and atoms
  - Increase with increasing mass



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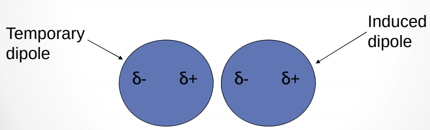
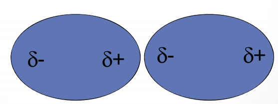
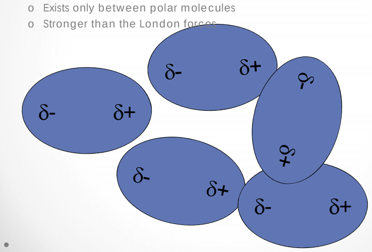


When the molecules get close, they distort each other's electron clouds, causing a temporary dipole.



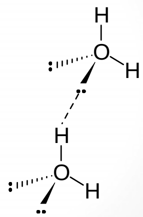
Kinds of attractive forces continued

- Dipole-dipole force
  - Exists only between polar molecules
  - Stronger than the London forces

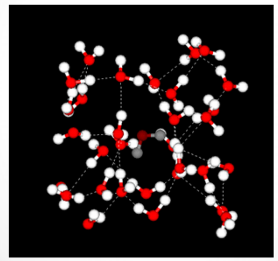


Kinds of attractive forces continued

- Hydrogen bonding
  - Requires a hydrogen attached to a very electronegative element (N, O or F)
  - Much stronger than London forces or Dipole-Dipole forces.
  - It is a weak covalent bond.

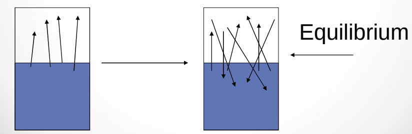


Hydrogen Bonding in Liquid water



Vapor Pressure and Boiling

- All substances have a vapor pressure
- It is the pressure of the vapor of the substance in equilibrium with the liquid.
- It increases with temperature



Boiling

- Boiling occurs when the vapor pressure of the liquid is equal to the external pressure above the liquid. This is dependent on the pressure.
- The ***normal boiling point*** is what is referred to when we say the boiling point. Here the vapor pressure is equal to one atmosphere of pressure.

Intermolecular forces and boiling point

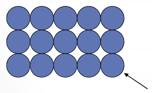
- The stronger the forces between the molecules the higher the boiling point.
- If the molecules are held together more tightly, it requires more energy to separate them.
- The stronger the forces, the lower the vapor pressure for the same reason.

Types of solids

- Molecular
  - Held together by the intermolecular forces just discussed
- Ionic
  - Held together by ionic bonds
- Metallic
  - Held together by metallic bonding
- Covalent network
  - Held together by covalent bonds

Metallic solids

- Non-directional bonding
  - Responsible for properties of metals, conductivity, malleability, etc.



Shares electrons with every other atom in the solid.

Covalent network solids

- Essentially just giant molecules
- Examples:
  - Diamond
  - Graphite
  - Silicon Carbide
  - quartz

Relative properties

- Metallic solids
  - Low to very high melting points
  - Malleable and Ductile
  - Conductive
- Covalent solids
  - Very high melting points
  - Brittle
  - Usually non-conductive.
- Molecular solids
  - Low melting points
  - Brittle
  - Non-conductive
- Ionic solids
  - Moderate to high melting points
  - Brittle
  - Non-conductive (except for liquid)