Energy Changes

Learning Objectives:

- Describe the meaning of enthalpy change in terms of exothermic (ΔH negative) and endothermic (ΔH positive) reactions.
- Describe bond breaking as endothermic process and bonding making as an exothermic process.
- Explain overall enthalpy changes in terms of the energy changes associated with the breaking and making of covalent bonds.
- Represent energy changes by energy profile and energy level diagrams, including reaction enthalpy changes and activation energies.

1 Introduction

- All chemical reactions involve energy changes.
- Some physical processes such as melting or dissolving of substances also involve energy changes.

1.1 Exothermic and Endothermic Changes

- Two experiments are carried out as shown in the table below. The temperature of the water is measured before and after adding the solid.

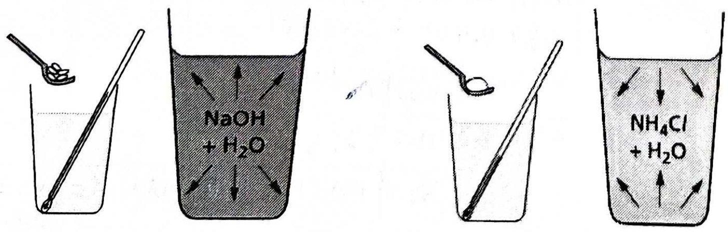
Experiment	Initial temperature (°C)	Final temperature (°C)	Temperature change (°C)
Dissolving of NaOH in water	28.0	34.5	increases (6.5)
Dissolving of NH_4Cl in water	28.0	22.0	decreases (6.0)

- When NaOH dissolves in water, the temperature increases and the mixture becomes hotter because heat is given out to the surroundings (from the chemical).

  This change is known as exothermic ~~en exothermi~~

- When NH_4Cl dissolves in water, the temperature decreases and the mixture becomes cooler because heat is taken in from the surroundings (by the chemical).

  This change is known as endothermic



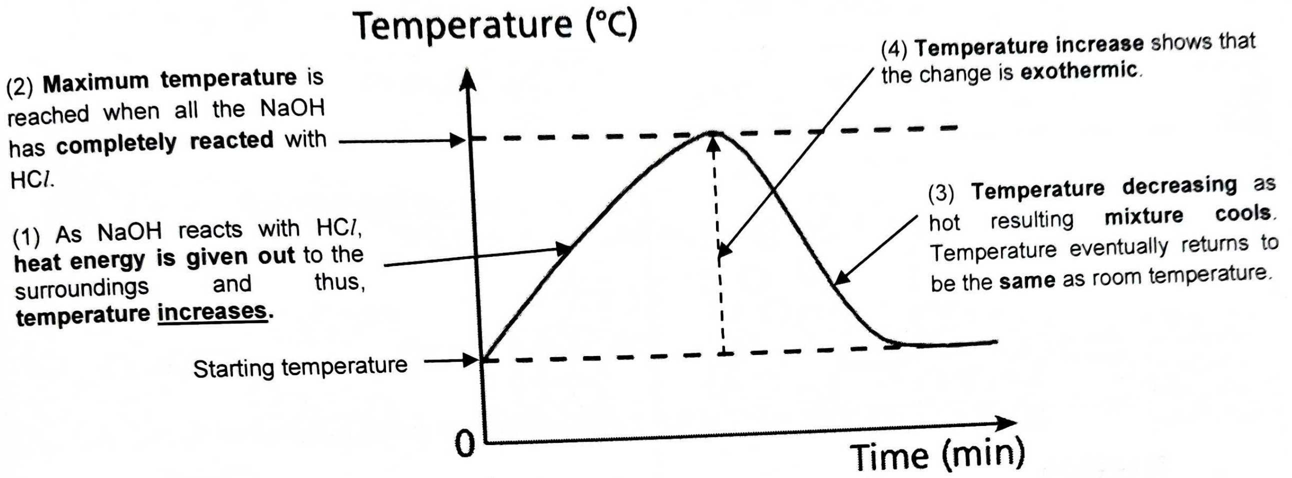
***Note:** The surroundings refer to the mixture, the container and the surrounding air.

An exothermic change is a change in which heat is given out **to the surroundings.**

An endothermic change is a change in which heat is taken in **from the surroundings.**

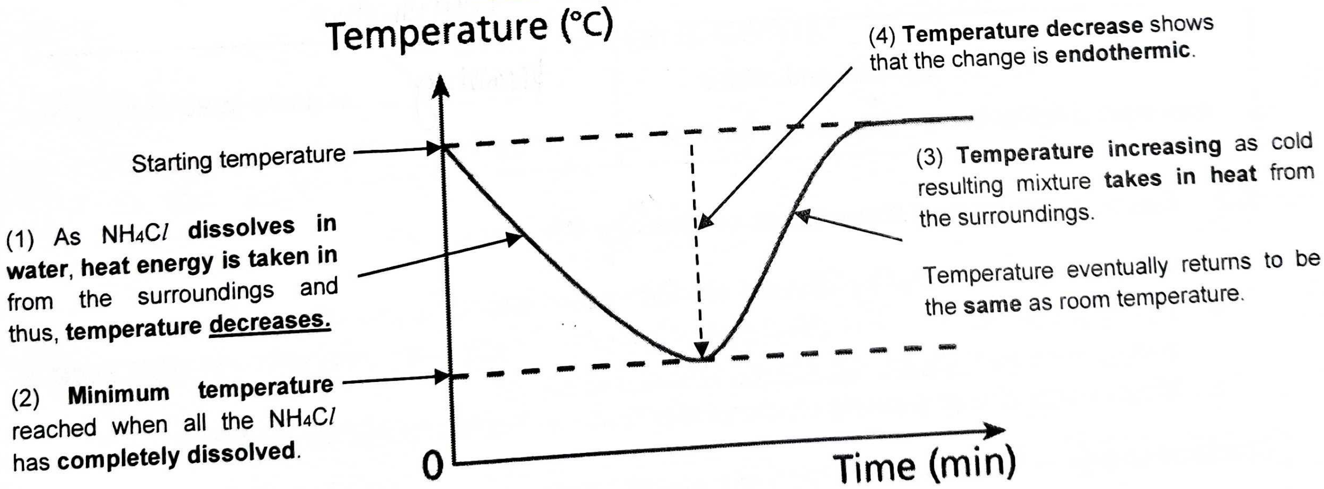
1.2 Temperature Variation for Exothermic and Endothermic Changes

- For **exothermic changes** such as **neutralisation reaction** between aqueous sodium hydroxide and hydrochloric acid, the temperature of the reaction mixture increases until the highest temperature is reached.
- When the reaction is complete, the temperature of the mixture decreases until it reaches room temperature.



- For **endothermic changes** such as **dissolving of ammonium chloride** solid in water, the temperature of the mixture decreases until the lowest temperature is reached.
- When the dissolving is complete, the temperature of the mixture increases until it reaches room temperature.

*** note: **dissolving** is **not** a chemical reaction but a physical change*



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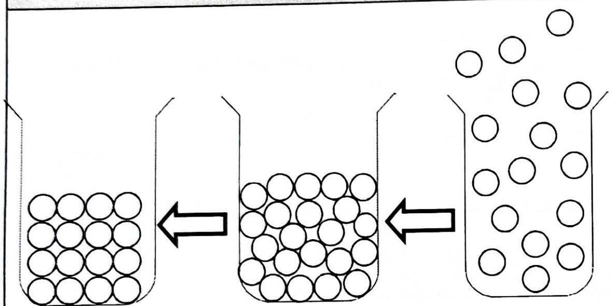
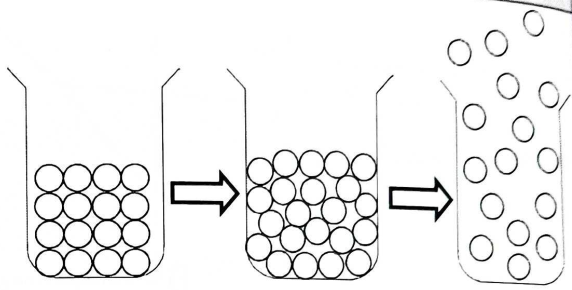
Exercise 1

Categorise the following **physical changes** into 'exothermic change' and 'endothermic change'.

Crystallisation	**Melting**	**Condensation**	**$CO_2(g) \rightarrow CO_2(s)$**	**Evaporation**
Freezing	**$H_2O(l) \rightarrow H_2O(g)$**	**Sublimation**	**$O_2(g) \rightarrow O_2(l)$**	**Boiling**

Exothermic Change	**Endothermic Change**
	
• Freezing ✓	• Melting ✓
• Condensation ✓	• Boiling ✓
• $CO_2(g) \rightarrow CO_2(s)$ ✓	• Evaporation ✓
• crystallisation ~~Sublimation~~ ✗	• $H_2O(l) \rightarrow H_2O(g)$ ✓
• $O_2(g) \rightarrow O_2(l)$ ✓	• Sublimation (solid to gas) ~~Crystallisation~~
Dilation ....of acids and alkalis	Dissolving ....of some ionic compounds
e.g. adding water to concentrated sulfuric acid.	e.g. ammonium chloride

1.3 Linking Chemical Reactions to Energy Changes

- All chemicals have energy stored in the form called **chemical potential energy**.
- During a chemical reaction, the chemical potential energy can be converted to other forms of energy such as heat, kinetic, sound, light and electrical.
- Most energy changes during chemical reactions involve heat [Unit: **kilojoules, kJ**]

Chemical energy → heat + light energy	Burning charcoal ($C + O_2 \rightarrow CO_2$)
Chemical energy → sound energy	Firecracker ($2\ C_7H_5N_3O_6 \rightarrow 3\ N_2 + 5\ H_2O + 7\ CO + 7\ C$)
Chemical energy → electrical energy	Batteries Reaction: Redox reaction → Movement of electrons
Chemiluminescence	Production of electromagnetic radiation (UV, IR or visible) observed when a chemical reaction causes an electronically excited intermediate or product

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1.4 Exothermic and Endothermic Changes in Chemical Reactions

- A chemical reaction is **exothermic** if **heat is given out to the surroundings** during the reaction.
- Common examples of chemical reactions that are **exothermic**:
  - **Combustion of fuels**
    Combustion reaction refers to the chemical reaction whereby a fuel such as hydrocarbons reacts with **oxygen in air.**

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(g)$$
$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$$

  - **Neutralisation reaction**

$$NaOH(aq) + HCl(aq) \rightarrow NaCl(aq) + H_2O(l)$$

  - **Reactions of acid with metals**

$$Mg(s) + H_2SO_4(aq) \rightarrow MgSO_4(aq) + H_2(g)$$

  - **Respiration**

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + ATP \rightarrow \text{heat}$$

- A chemical reaction is **endothermic** if **heat is taken in from the surroundings** during the reaction.
- Examples of chemical reactions that are endothermic:
  - **Thermal Decomposition of compounds**
    Decomposition is the process whereby a substance breaks down into two or more simpler substances.

$$2Cu(NO_3)_2(s) \rightarrow 2CuO(s) + 4NO_2(g) + O_2(g)$$
$$CaCO_3(s) \rightarrow CaO(s) + CO_2(g)$$

  - **Photosynthesis** (produces ATP)

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$

endothermic : sunlight is absorbed

Exercise 2

1. The scheme shows four stages, I to IV, in the conversion of solid candlewax, $C_{30}H_{62}$, into carbon dioxide and water.

I.	$C_{30}H_{62}(s) \rightarrow C_{30}H_{62}(l)$ endothermic
II.	$C_{30}H_{62}(l) \rightarrow C_{30}H_{62}(g)$ endothermic
III.	$2C_{30}H_{62}(g) + 91O_2(g) \rightarrow 60CO_2(g) + 62H_2O(g)$ exothermic [combustion]
IV.	$30CO_2(g) + 31H_2O(g) \rightarrow 30CO_2(g) + 31H_2O(l)$ exothermic

The stages that are endothermic: ~~III~~ I , II ....

2. Which of the following equations show exothermic reactions?

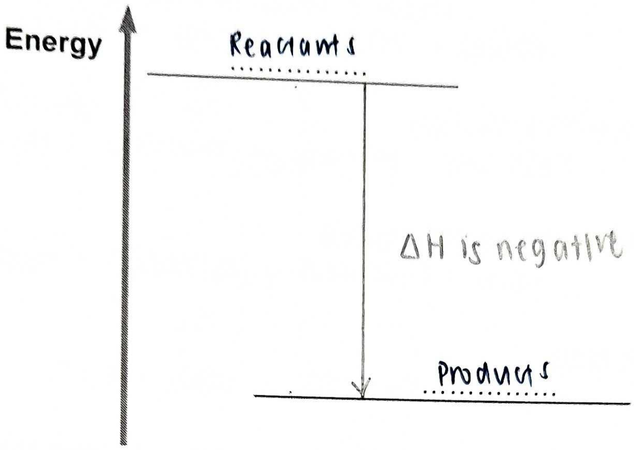
I.	$H^+ + OH^- \rightarrow H_2O$ Neutralisation
II.	$Zn + 2H^+ \rightarrow Zn^{2+} + H_2$ metal acid
III.	$C + O_2 \rightarrow CO_2$ combustion
IV.	$FeCO_3 \rightarrow FeO + CO_2$ Thermal decomposition

The equations that show exothermic reactions: I, II, III ....

2 Energy Level Diagrams for Exothermic and Endothermic Reactions

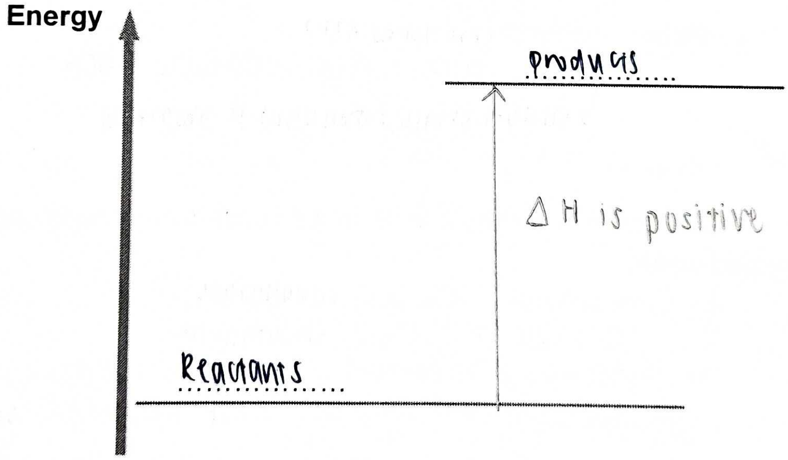
2.1 For exothermic reactions, the **product(s)** have <u>lower</u> energy than the **reactant(s).**

- The difference between the energy levels of the product(s) and the reactant(s) is equal to the ...~~even~~ energy given out... to the surroundings during the reaction.
- The energy change is ..negative........



2.2 For endothermic reactions, the **product(s)** have <u>higher</u> energy than the **reactant(s).**

- The difference between the energy levels of the product(s) and the reactant(s) is equal to the ...energy taken in ~~from the surroundings~~... from the surroundings during the reaction.
- The energy change is ..positive........



Summary

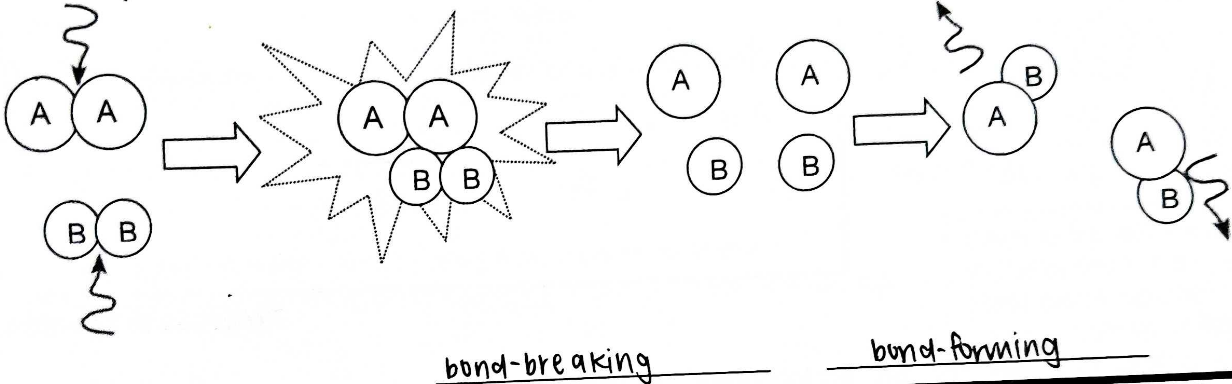
	Exothermic Change	Endothermic Change
1	Heat is ...given out to.... the surroundings.	Heat is ....~~taken~~ taken in from.....the surroundings
2	There is an .....increase........ in the temperature of the mixture.	There is a ....decrease........ in the temperature of the mixture.
3	Energy level of products is ..lower.......... than energy level of reactants.	Energy level of products is ....higher........ than energy level of reactants.

3 Bond Energy and Enthalpy Change

3.1 Bond Breaking and Bond Forming in a Chemical Reaction

- In any chemical reaction, when reactants react to form products, the following occurs:
  1. The reacting particles must ......collide............ with each other.
  2. The bonds in the reactants have to be broken (...bond-breaking..................). ~~endotherm~~ endothermic
  3. The new bonds between atoms have to form, which lead to the formation of products (...bond-forming.....................). exothermic

Example: $A_2 + B_2 \rightarrow 2AB$



- When bonds between atoms in reactants are broken, heat energy is **absorbed**.
- Thus, **bond breaking** is an **<u>endothermic change</u>**.
- When bonds between atoms in products are formed, heat energy is **released**.
- Thus, **bond forming** is an **<u>exothermic change</u>**.

3.2 Enthalpy Change in Exothermic and Endothermic Reactions

- The **overall heat change** in a reaction is known as ...enthalphy change.................... The symbol is ...~~kilojoules~~ ΔH and it is measured in **<u>kJ</u>**. Kilojoules.
- **For **exothermic** reaction, ΔH has a ..negative........value. **For **endothermic** reaction, ΔH has a ..positive.................. value.
- Bonding breaking (**endothermic** change) and bond forming (**exothermic** change) occurs in every chemical reaction.

3.2.1 The ΔH for an **exothermic reaction** is a **negative** value because the **energy released/given out** during bond forming in products is more than the **energy absorbed/taken in** during bond breaking in reactants

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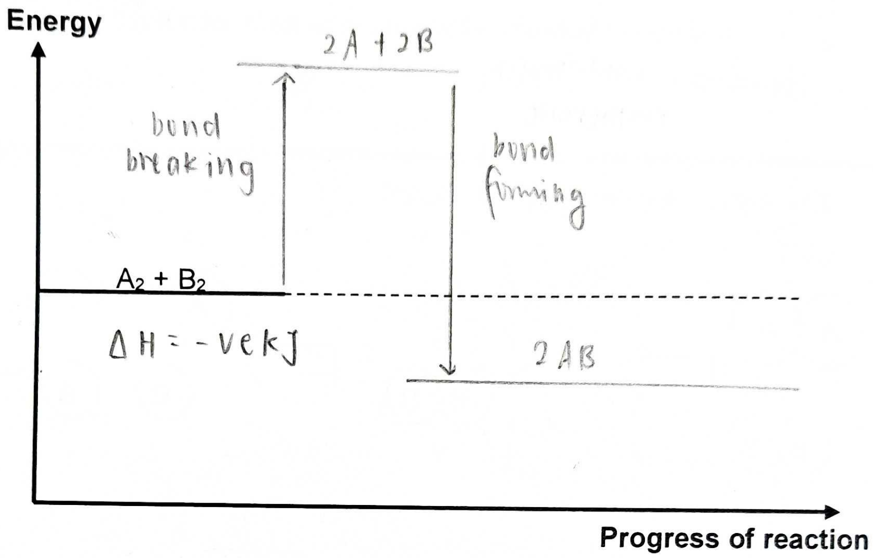
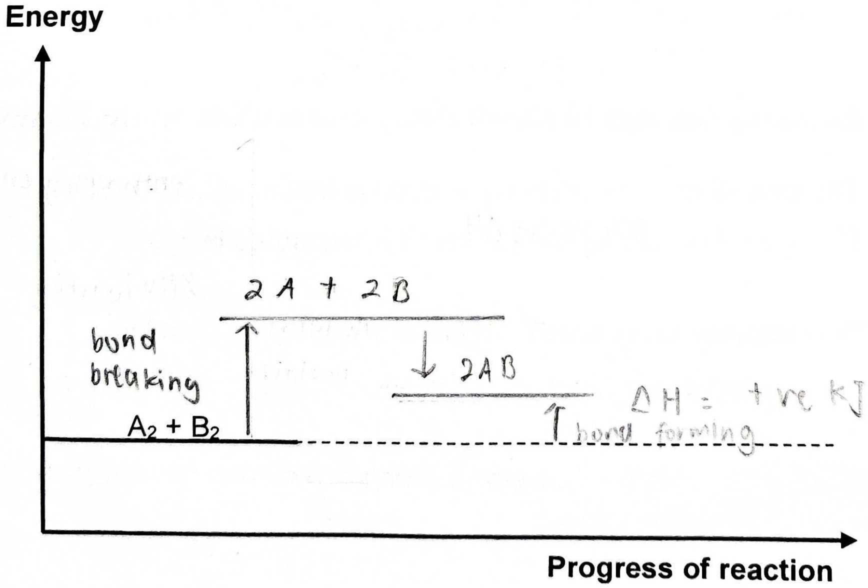
- Overall, the energy is **given out** the surroundings and the **energy level of products** is **lower** than that of the **reactants**.



3.2.2 The ΔH for an **endothermic reaction** is a **positive** value because the **energy released/given out** during **bond forming** in products is less than the **energy absorbed/taken in** during **bond breaking** in reactants

- Overall, the energy is **taken in from** the surroundings and the energy level of products is **higher** than that of the reactants.



3.2.3 Calculating the **enthalpy change, ΔH** of a chemical reaction:

- **Enthalpy change (ΔH) =** Total energy change in bond breaking **+** Total energy change in bond forming
- For exothermic reaction, ΔH has a **negative** value.
- For endothermic reaction, ΔH has a **positive** value.

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3.3 Bond Energy and Calculation of Enthalpy Change

- **Bond energy** is the **energy absorbed** to **break one mole of covalent bonds**. It is measured in **kJ/mol.**
- The energy released to form one mole of the same covalent bonds has **the same value**.
- Examples of bond energies are given below:

Covalent bond	Bond energy (kJ/mol)	Example of molecules containing the bond
H – H	436	Hydrogen, H_2
O – H	463	Water, H_2O
O = O	496	Oxygen, O_2

- Interpretation of bond energy, using hydrogen as example:
  - The energy change in breaking one mole of H – H bonds is **+436 kJ.**
    H – H → 2H
  - The energy change in forming one mole of H – H bonds is **- 436 kJ.**
    2H → H – H

What is the difference in the energy change in bond breaking and energy change in bond forming of one mole of H – H bonds?

Question:
Show, by calculation, that the reaction between hydrogen and oxygen gas to produce steam is an exothermic reaction.

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(g)$$

Step1: Identify all the bonds in reactants (to be broken) and in products (to be formed).

$2H_2$	+	O_2	→	$2H_2O$
H – H		O = O		H – O – H
H – H				H – O – H

Bonds in reactants (to be broken): …….. moles of … moles of H – H bonds and … moles of O = O bonds

Bonds in product (to be formed): … moles of O – H bonds.

Step 2: Calculate the energy change in bond breaking in reactants.

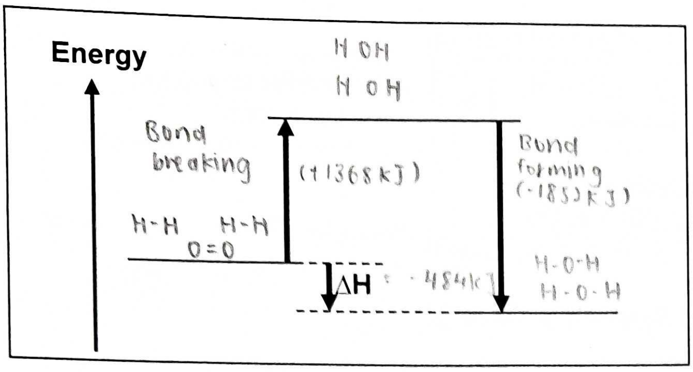
Energy change in bond breaking = ~~+2+~~ (2 x (+436)) + (1 x (+496)) = + 1368 kJ

Step 3: Calculate the energy change in bond forming in products.

Energy change in bond forming = 4 x (-463) = -1852 kJ

Step 4: Calculate overall heat change (enthalpy change) by adding up the energy change during bond breaking to the energy change in bond forming.

Enthalpy change, ΔH = +1368 + (-1852) = -484 kJ



The overall heat change or enthalpy change for this reaction is -484kJ (negative value).

Thus, the reaction is exothermic

Note:

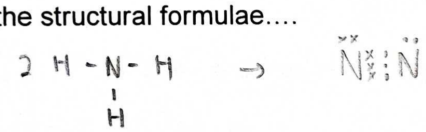
Exothermic Change	Include - sign?	Endothermic Change	Include + sign?
"Energy change"	Yes	"Energy change"	Yes
"Energy released" / "Energy given out"	No	"Energy absorbed" / "Energy taken in"	No

Exercise 3

1. Ammonia gas decomposes to give hydrogen gas and nitrogen gas as shown in the equation below.

$$2NH_3(g) \rightarrow N_2(g) + 3H_2(g)$$

Hint: Draw the structural formulae....



Given the following values of bond energy, show by calculation, that this decomposition is an endothermic reaction.

Bond	Bond Energy (kJ/mol)
N – H	393
N ≡ N	941
H – H	436
N – N	160

Working:

- **Energy change in bond breaking** = 2 (3 (+393))
  = +2358 kJ
- **Energy change in bond forming** = ~~(-941)~~ (-941) + 3(-436)
  = -2249 kJ
- **Enthalpy change of reaction, ΔH** = +2358 + (-2249)
  = +109 kJ
- Since ΔH is a Positive value, the reaction is endothermic

2. The formation of hydrogen iodide from hydrogen and iodine is an endothermic reaction.

$$H-H + I-I \rightarrow H-I + H-I$$

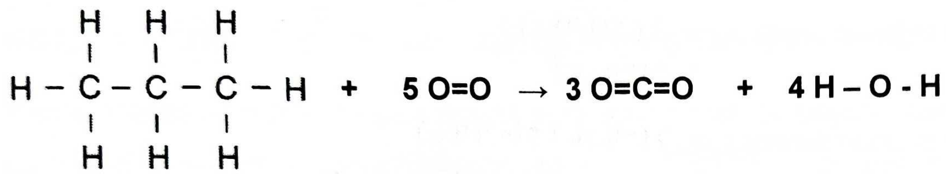
What can be deduced from this information?

A The number of bonds broken is greater than the number of bonds formed.
B The formation of H – I bonds absorb energy.
C The products possess less energy than the reactants.
D The total energy change in bond formation is less than that in bond breaking.

D

3. Propane undergoes complete combustion as shown in the following reaction.

$$C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(l)$$



2C-C
8C-H

Given the bond energy values in the table below and that the enthalpy change of the combustion reaction is -1660 kJ, calculate the **C – C bond energy**.

Bond	Bond Energy (kJ/mol)
C – H	410
C = O	740
C – O	358
O = O	496
O – H	460

- Let the **C-C bond energy** be y **kJ/mol**

Note that the unit for **Enthalpy change of reaction, ΔH is kJ;

while the unit for **Bond energy Is kJ/mol**

- **Energy change in bond breaking** = 8 (+410) + 2(+y) + 5(+496)
  = (+5760) + (+2y)

- **Energy change in bond forming** = 3 [2 (-740)] + 4 [2 (-460)]
  = -8120 kJ

- Hence,

$$\Delta H = (+5760) + (+2y) + (-8120)$$
$$-1660 = -2360 + (+2y)$$
$$y = 350$$

- Therefore, **C-C bond energy** is ...350............... kJ/mol

3.3 Enthalpy Change of Forward Reaction Versus Backward Reaction

- In the earlier section 3.3, the calculated value of enthalpy change for the reaction, $2H_2(g) + O_2(g) \rightarrow 2H_2O(g)$, is -484 kJ.

Question:
Calculate the enthalpy change for the following reaction.

$$2H_2O(g) \rightarrow 2H_2(g) + O_2(g)$$

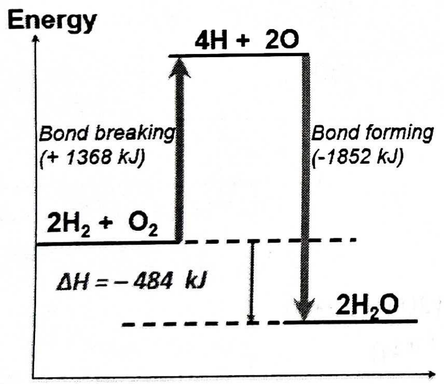
Covalent bond	Bond energy (kJ/mol)
H – H	436
O – H	463
O = O	496

- Energy change in bond breaking = 2(2(+463))
  = +1852kJ
- Energy change in bond forming = 2(-436)+(-496)
  = ~~-1380kJ~~ -1368kJ
- Enthalpy change of reaction, ΔH = +1852kJ - (-1368kJ)
  = +484kJ

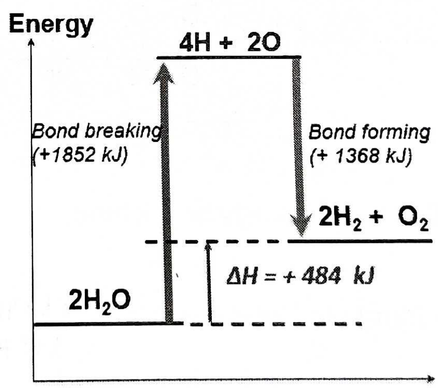
What do you notice?

- If the forward reaction is exothermic, the backward reaction will be endothermic...... and vice versa.
- The magnitude of the enthalpy change remains the same.........

$2H_2(g) + O_2(g) \rightarrow 2H_2O(g)$



$2H_2O(g) \rightarrow 2H_2(g) + O_2(g)$



Exercise 4

1. The Earth atmosphere contains ozone, O_3. The ozone absorbs ultraviolet light and breaks down to form oxygen. The enthalpy change (ΔH) for the reaction is -143 kJ.

$$2O_3(g) \rightarrow 3O_2(g)$$

(i) **Explain, in terms of bond breaking and bond forming, why the reaction is exothermic.

Energy released to form the bonds in the products is ~~greater~~ more than energy absorbed to break the bonds in reactants.

(ii) What is the value of ΔH for the reaction, $3O_2(g) \rightarrow 2O_3(g)$?

+143kJ

3.4 Interpretation of Energy Change from Given Equations

For exothermic reaction, the enthalpy change or ΔH has a negative **value.**

For endothermic reaction, the enthalpy change or ΔH has a positive **value.**

Exothermic

E.g. 1 Consider the following reaction.

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g) \qquad \Delta H = -882\ kJ$$

- Interpretation:

  When **one mole** of methane gas reacts with two moles of oxygen gas to form one mole of carbon dioxide gas and two moles of steam, 882kJ of heat energy is given out to the surroundings or the enthalpy change is -882kJ

  If **two moles** of methane gas reacts with four moles of oxygen gas to form two moles of carbon dioxide gas and four moles of steam, 1764kJ of heat energy is given out to the surroundings or the enthalpy change is -1764kJ

Try this:

What is the enthalpy change if 8.0 g of CH_4 is reacted?

No. of moles of $CH_4 = \frac{8}{12.0+(1.0\times4)}$

$= \frac{8}{16.0}$

$= 0.500$ mol

Enthalpy change $= 0.500 \times (-882)$

$= -441$ kJ

Endothermic

E.g. 2 Consider the following reaction.

$$N_2(g) + O_2(g) \rightarrow 2NO(g) \qquad \Delta H = +18kJ$$

- Interpretation:

  When **one mole** of nitrogen gas reacts with one mole of oxygen gas to form two moles of nitrogen monoxide gas, 18kJ of heat energy is taken in from the surroundings or the enthalpy change is +18 kJ

  If **half a mole** of nitrogen gas reacts with half a mole of oxygen gas to form one mole of nitrogen monoxide gas, 9kJ of heat energy is taken in from the surroundings or the enthalpy change is +9kJ

Try this:

What is the enthalpy change if 12.0 dm^3 of NO is formed at r.t.p.?

No. of moles of NO $= \frac{12.0}{24.0}$

$= 0.500$ mol

Enthalpy change $= \frac{+18}{2} \times 0.500$

$= +4.50$ kJ

Exercise 5

Hydrogen gas reacts with chlorine gas as shown by the equation below.

$$H_2(g) + Cl_2(g) \rightarrow 2HCl(g) \qquad \Delta H = -178 \text{ kJ}$$

Interpretation: When ***one mole*** *of $H_2(g)$ reacts with* ....1mole.... *of $Cl_2(g)$ to form* ....2 moles.... *of HCl(g), ΔH is -178 kJ*

(i.e. energy given out/ released to the surrounding is 178 kJ)

Calculate:

(i) the energy change when 14.2 g of chlorine gas reacts completely with hydrogen gas.

No. of moles of Cl_2 reacted = $14.2 \div 71.0$

$= 0.200$ mol

Energy change = $0.200 \times (-178)$

$= -35.6$ kJ //

(ii) the energy released when 4.00 moles of hydrogen chloride gas is formed.

Energy released = $(4.00 \div 2) \times 178$

$= 356$ kJ

(iii) the energy released when 1.00 g of hydrogen gas is allowed to react with 1.00 g of chlorine.

No. of moles of H_2 given = $\frac{1.00}{2.0} = 0.500$ mol

No. of moles of Cl_2 given = $\frac{1.00}{71.0} = 0.014085$ mol

$$\frac{\text{no. of moles of } Cl_2}{\text{no. of moles of } H_2} = \frac{1}{1}$$

No. of moles of Cl_2 needed if H_2 is used up = 0.500

No. of moles of Cl_2 needed ....>.... no. of moles of Cl_2 given

Hence, ...Chlorine.... is the limiting reactant.

Energy released = 0.014086×178

$= 2.51$ kJ //

4 Activation Energy and Energy Profile Diagrams

4.1 Activation Energy

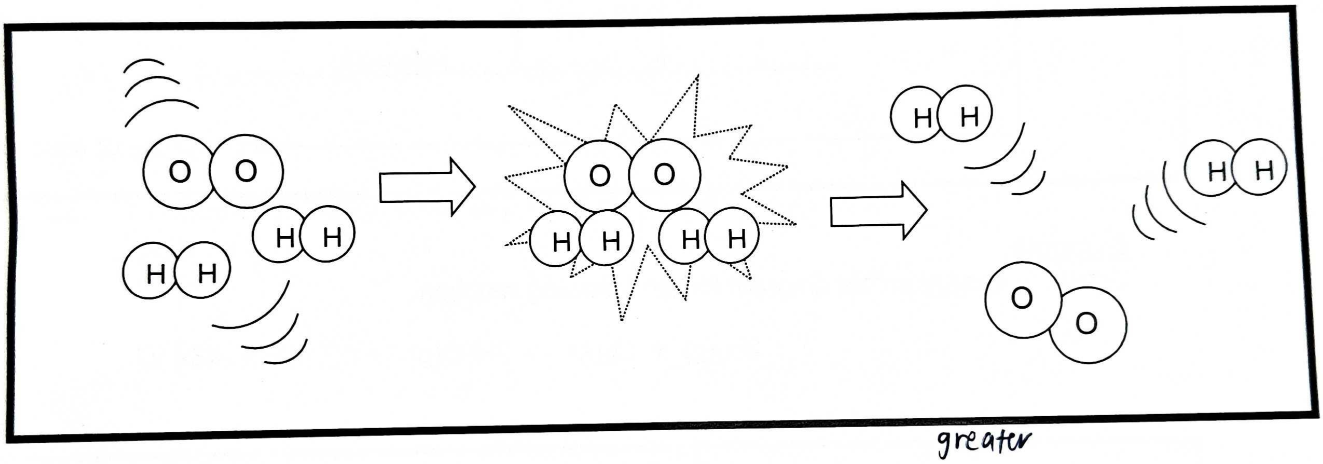
Recall: for a reaction to occur, the reacting particles must collide with each other so that the bond breaking and bond forming can take place.

However, not every collision leads to breaking of the bonds in reactants.

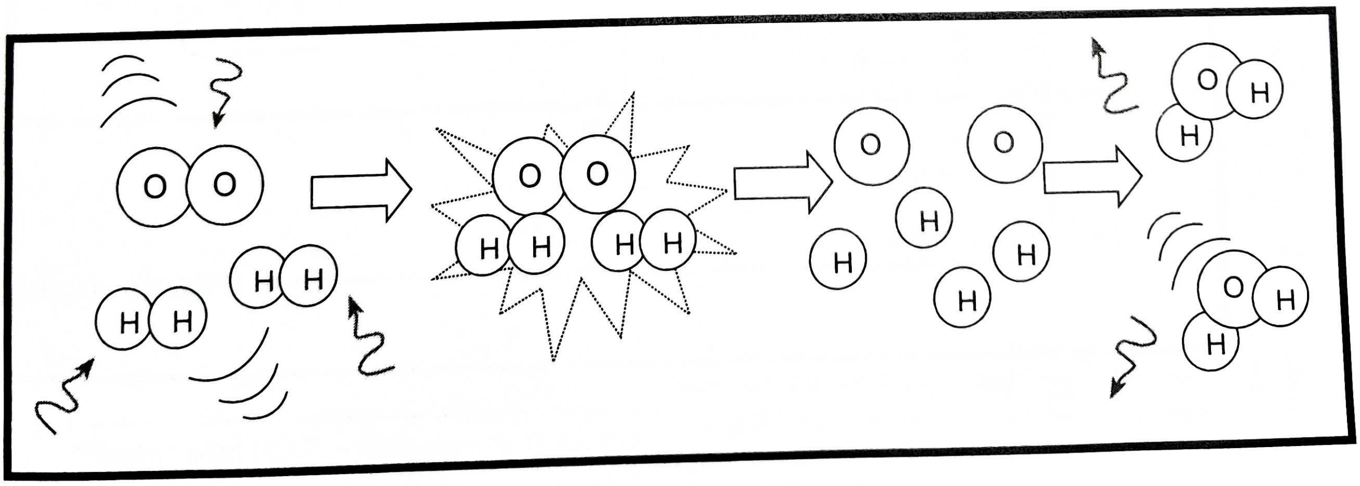
...Activation energy.............is the ....minimum...............amount of energy that reacting particles must possess in order for a chemical reaction to occur.

Symbol for activation energy is ....Ea.......... and it is measured in ......kJ........

If the reacting particles possess energy ....less........... than the activation energy, the bonds in reactants will not be broken upon collision. Hence, there will be no formation of products.



- Upon absorbing energy from surroundings, reactants have energy ...~~less~~ greater.......... than, or ..equal to.......... the activation energy, the bonds in reactants will be broken upon collision.



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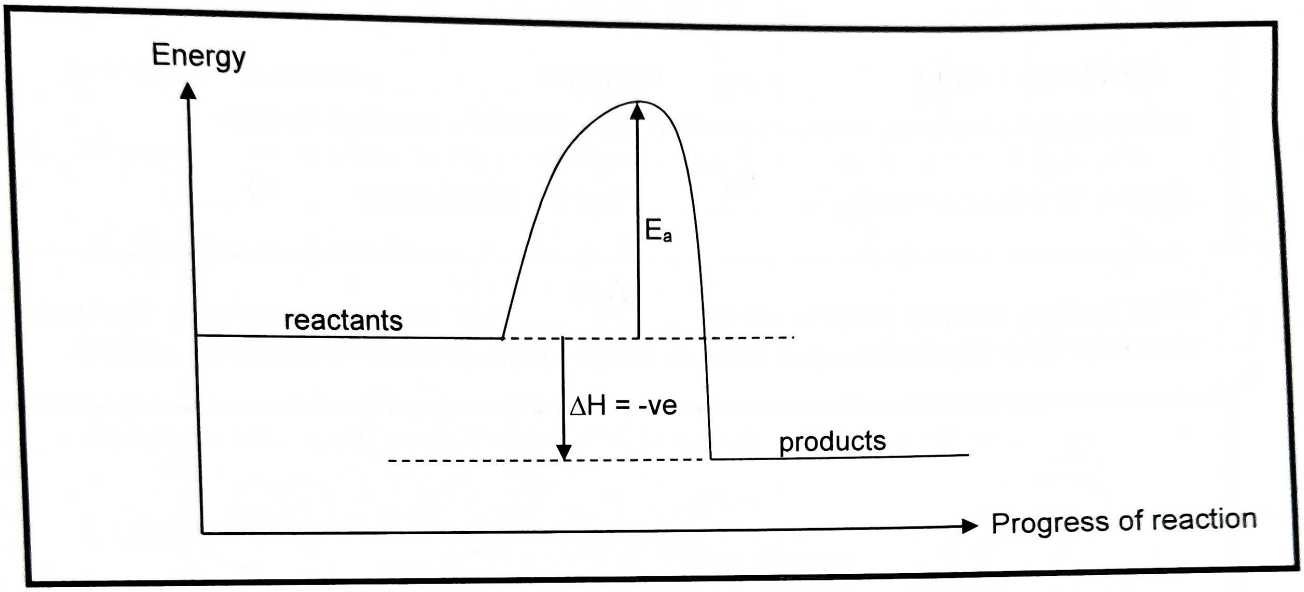
4.2 Energy Profile Diagrams

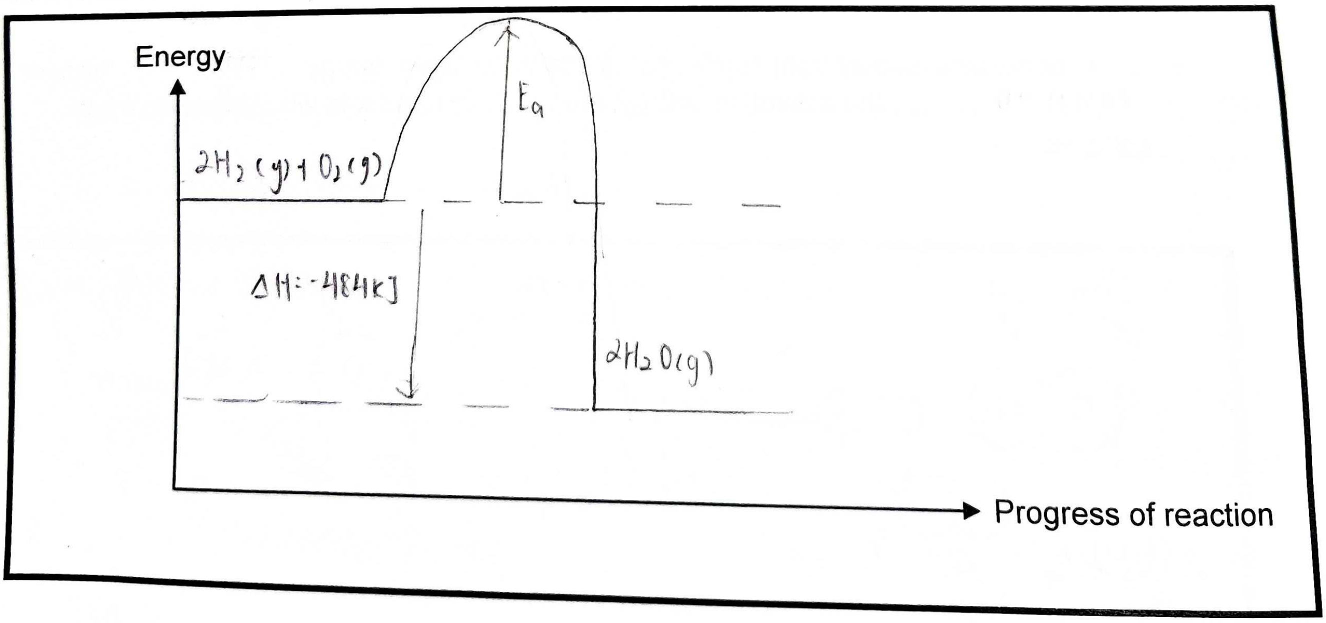
Energy profile diagrams are used to show the energy changes that occur during a chemical reaction, including the activation energy for the reaction.

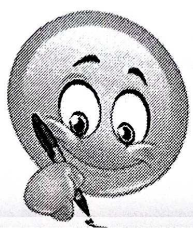
4.2.1 For exothermic reaction:



Example:
Draw the energy profile diagram for the following reaction.

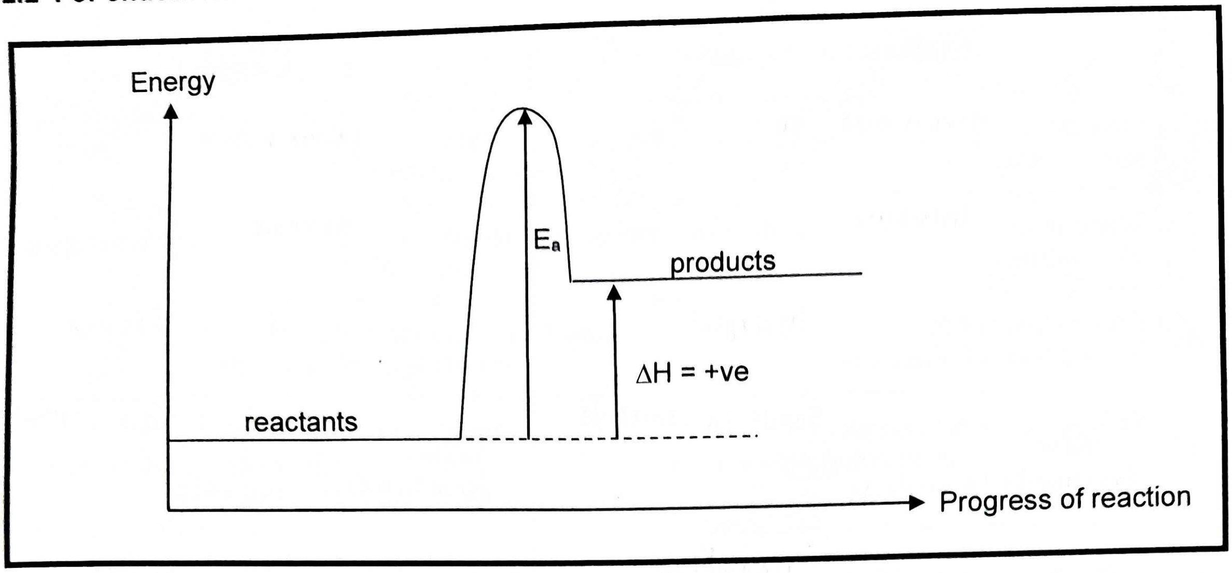
$$2H_2(g) + O_2(g) \rightarrow 2H_2O(g) \qquad \Delta H = -484\ kJ$$





Check your own work – "Did I label these?"
- E_a
- ΔH
- Reactants and products (according to balanced equation) with state symbols

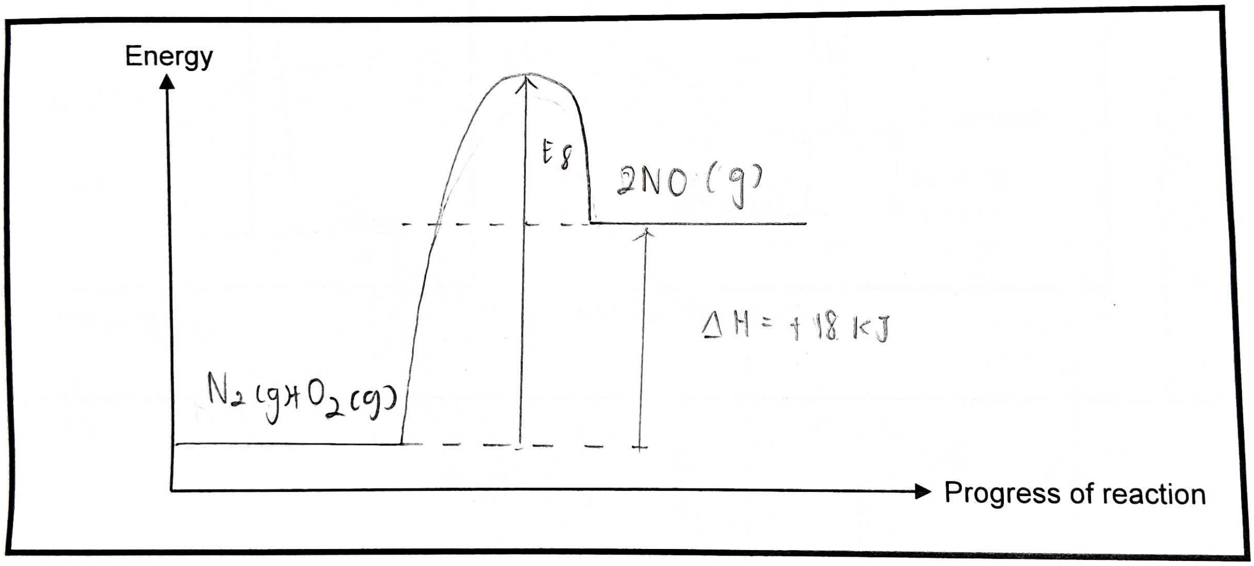
4.2.2 For endothermic reaction:

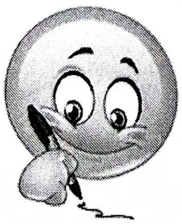


Example:

Draw the energy profile diagram for the following reaction.

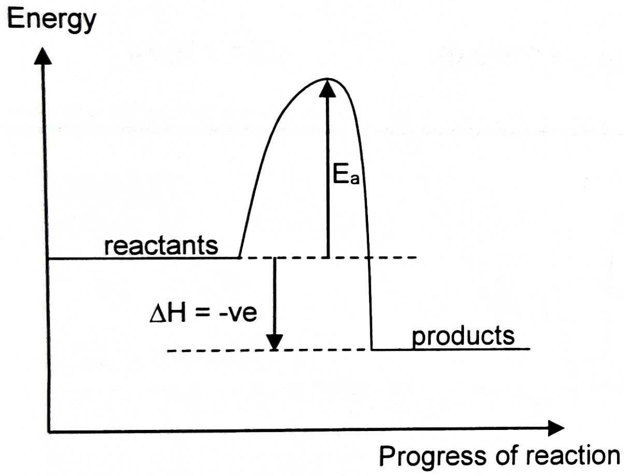
$N_2(g) + O_2(g) \rightarrow 2NO(g)$ $\Delta H = +18$ kJ





Check your own work – "Did I label these?"
- E_a
- ΔH
- Reactants and products (according to balanced equation) with state symbols

5 Summary

	Exothermic Change	Endothermic Change
1	Heat is ......given out to............ the surroundings.	Heat is ......taken in from........ the surroundings.
2	There is an ...increase....... in the temperature of the mixture.	There is a ....decrease..... in the temperature of the mixture.
3	Energy level of products is lower........... than energy level of reactants.	Energy level of products is ...higher....... than energy level of reactants.
4	Energy taken in to break ...bonds in reactants... is ...lower....... than energy given out to ...form bonds in products	Energy taken in to break ...bonds in reactants....is ...higher...... than energy given out to ...form bonds in products.
5	Enthalpy change (ΔH) is .....negative.....	Enthalpy change (ΔH) is ..positive.......
6	Energy profile diagram: 	Energy profile diagram: