Anderson Serangoon Junior College
JC2 H2 Chemistry
HALOGEN DERIVATIVES

Learning Outcomes

Candidates should be able to:

(a) recall the chemistry of halogenoalkanes as exemplified by
  (i) the following nucleophilic substitution reactions of bromoethane: hydrolysis; formation of nitriles; formation of primary amines by reaction with ammonia
  (ii) the elimination of hydrogen bromide from 2−bromopropane

(b) describe and explain the mechanisms of nucleophilic substitutions in halogenoalkanes
  (i) S_N1, in terms of stability of the carbocation intermediates
  (ii) S_N2, in terms of steric hindrance of the halogenoalkanes

(c) explain the stereochemical outcome in nucleophilic substitution involving optically active substrates:
  (i) inversion of configuration in S_N2 mechanism
  (ii) racemisation in S_N1 mechanism

(d) interpret the different reactivities of halogenoalkanes, with particular reference to hydrolysis and to the relative strengths of the C−Hal bonds

(e) explain the unreactivity of chlorobenzene compared to halogenoalkanes towards nucleophilic substitution, in terms of the delocalisation of the lone pair of electrons on the halogen and steric hindrance

(f) suggest characteristic reactions to differentiate between:
  (i) different halogenoalkanes
  (ii) halogenoalkanes and halogenoarenes e.g. hydrolysis, followed by testing of the halide ions

(g) explain the uses of fluoroalkanes and fluorohalogenoalkanes in terms of their relative chemical inertness

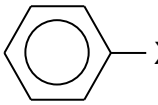
(h) recognise the concern about the effect of chlorofluoroalkanes (CFCs) on the ozone layer
[the mechanistic details of how CFCs deplete the ozone layer are **not** required]

References

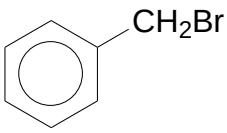
1. Chemistry for Advanced Level by P. Cann & P. Hughes
2. Organic Chemistry (6th edition) by McMurry
3. A−Level Chemistry by E.N. Ramsden
4. Understanding Chemistry for Advanced Level by Ted Lister and Janet Renshaw
5. Chemistry in Context by Graham Hill and John Holman

1. INTRODUCTION

- Halogen derivatives are a homologous series of organic compounds containing **one or more** halogen atoms.
- General formula: $\underline{\mathbf{C_nH_{2n+1}X}}$ (where X = F, C*l*, Br or I).
- They are important intermediates in organic synthesis.
- 2 types: **halogenoalkanes and halogenoarenes**

Halogenoalkanes (or alkyl halides)	Halogenoarenes (or aryl halides)
R−X where **R** is an alkyl group such as $-CH_3$, $-CH_2CH_3$	 or Ar-X X is a substituent in the benzene ring
X is a halogen atom, an element from Group 17 e.g. F, C*l,* Br, I.	

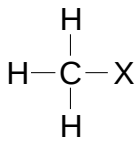
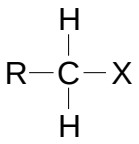
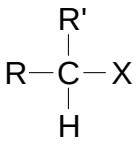
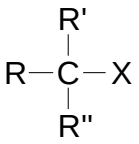
Checkpoint 1: Circle the correct classification for the following compound.



Alkyl halide **Aryl halide**

Note: *The C atom in the $-CH_2Br$ group, being the immediate carbon bonded to the benzene ring, is known as a benzyl carbon.*

- Halogenoalkanes are classified as **primary (1°)**, **secondary (2°)** or **tertiary (3°)**, depending on the number of R groups/carbon atoms attached to the carbon bonded to the halogen.

Methyl (1°)	Primary (1°)	Secondary (2°)	Tertiary (3°)
No R group	1 R group	2 R groups	3 R groups
			

Note: *the groups R, R' and R'' may or may not be the same.*

2. NOMENCLATURE

- The halogen atom is considered as a *substituent*.
- *Prefixes* (fluoro−, chloro−, bromo− and iodo−) are used together with numbers, where necessary, to show the position of the halogen atom in the molecule.

$CH_3CH(Br)CH_3$

chloroethane 2−bromopropane chlorobenzene

- If there are 2 or more halogen atoms of the same kind, *prefixes* (di−, tri−, tetra−, etc.) are used to indicate the number of halogen atoms present.

1,2−dichloroethane 1,1,2−trichloropropane 1,2,4−trichlorobenzene

- When a compound contains 2 or more different halogen atoms the substituents are numbered in alphabetical order.

3−chloro−2−iodohexane

Checkpoint 2: Write the structural formula and IUPAC names of the following compounds.

2−chloro−2−methylpropane		
2,4−dichloromethylbenzene	(bromomethyl)benzene/ benzyl bromide	

3. PHYSICAL PROPERTIES OF HALOGENOALKANES AND HALOGENOARENES

3.1 Boiling Point

1. Halogenoalkanes have <u>higher</u> boiling points (lower volatility) than alkanes of the same number of carbon atoms

e.g.

Compound	$CH_3CH_2CH_3$	$CH_3CH_2CH_2Br$
Boiling point/ K	231	344

There is **stronger permanent dipole – permanent dipole attractions** between polar $CH_3CH_2CH_2Br$ molecules.

In addition, the greater number of electrons / greater size of the electron cloud results in greater ease of distortion of electron cloud in $CH_3CH_2CH_2Br$. Hence there is **stronger instantaneous dipole−induced dipole attractions** (id-id) between $CH_3CH_2CH_2Br$ molecules.

More energy is required to overcome the stronger intermolecular forces between $CH_3CH_2CH_2Br$ than the **weaker id-id attractions** between $CH_3CH_2CH_3$.

2. Boiling point of halogenoalkanes in a homologous series **<u>increases</u>** with the length of the carbon chain

e.g.

Compound	CH_3Cl	CH_3CH_2Cl	$CH_3CH_2CH_2Cl$
Boiling point/ K	249	285	320

As the length of the alkyl chain increases, the **number of electrons / electron cloud size increases**, which results in a **greater ease of distortion of the electron cloud**. More energy is required to overcome the **stronger instantaneous dipole–induced dipole attractions between the molecules**.

3. Boiling point **<u>increases</u>** down the halogen group in halogenoalkanes and halogenoarenes

e.g.

Compound	CH_3CH_2F	CH_3CH_2Cl	CH_3CH_2Br	CH_3CH_2I
Boiling point/ K	235	285	312	345

e.g.

Compound	C_6H_5F	C_6H_5Cl	C_6H_5Br	C_6H_5I
Boiling point/ ^oC	85	132	156	189

The **number of electrons / electron cloud size increases**, which results in a **greater ease of distortion of the electron cloud**. More energy is required to overcome the **stronger instantaneous dipole–induced dipole attractions between the molecules**.

4. For structural isomers, the order of the boiling point is $1^o > 2^o > 3^o$ halogenoalkanes

e.g.

	1^o	2^o	3^o
Compound	$CH_3CH_2CH_2CH_2Br$	$CH_3CH_2CHBrCH_3$	$C(CH_3)_3Br$
Boiling point/ K	375	364	346

The **surface area for contact** between molecules **decreases** as the shapes of the molecules change from **elongated** (1^o) **to more spherical** (3^o) shape. Less energy is required to overcome the weaker instantaneous dipole−induced dipole forces of attraction between the molecules.

3.2 Solubility

In order for a compound to be soluble in a solvent, the energy released to form the solvent−solute attraction must be able to compensate for the energy taken in to overcome the solute−solute and solvent–solvent attractions.

Although halogenoalkanes (RX) molecules and halogenoarenes (ArX) are polar (due to the presence of the polar C−X bond), they are in general

1. soluble in non-polar solvents like benzene and CCl_4

2. insoluble in polar solvents like water.

The energy released to form *instantaneous dipole−induced dipole and permanent dipole−permanent dipole forces of attraction* between RX (or ArX) molecules and water molecules is insufficient to compensate for the energy taken in to overcome the *hydrogen bonds* present between water molecules.

Checkpoint 3

RX molecules with longer carbon chains are less soluble in water than those which have shorter ones. Why? (Hint: Why is the solute−solute interaction stronger among RX molecules with longer carbon chains?)

RX molecules with longer carbon chains have more _____ and hence _____ _____ attractions between them.

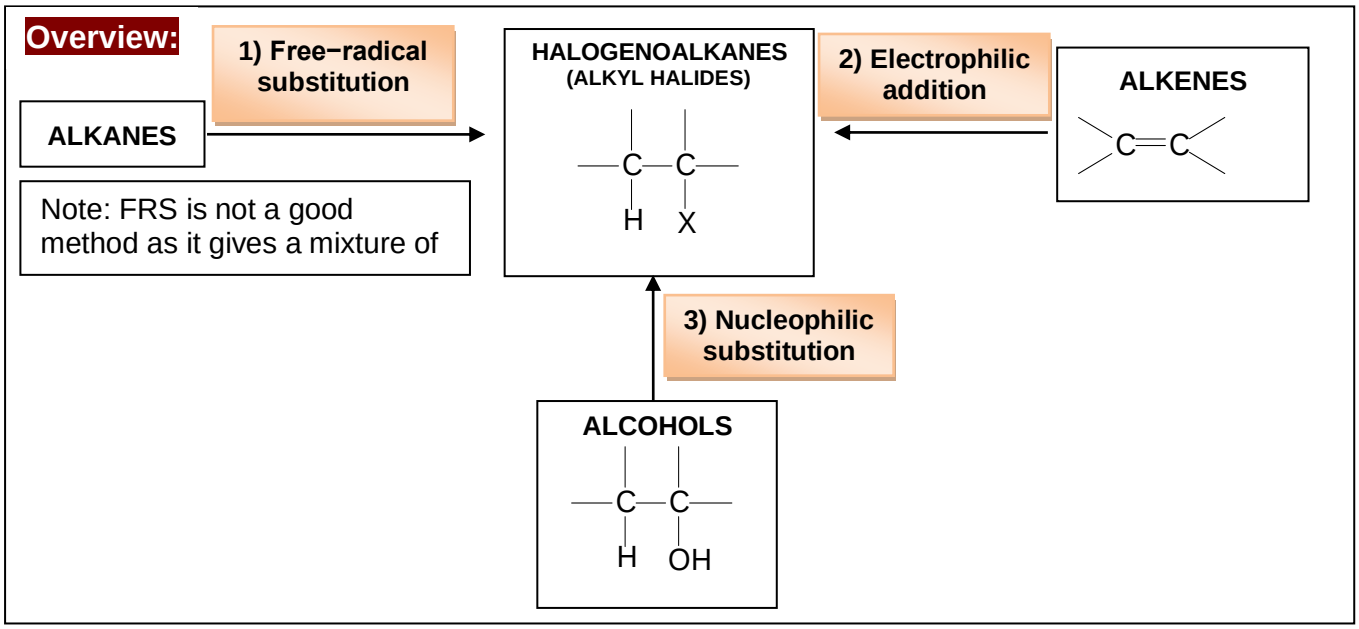
Thus, the energy _____ when the _____ attractions formed between RX and water molecules is _____ to overcome the _____ _____ attractions between RX molecules.

(I) HALOGENOALKANE

4. PREPARATION OF HALOGENOALKANE

How are halogenalkane synthesised?

Halogenoalkane can be obtained from three main groups of organic compounds, namely, alkanes, alkenes and alcohols.



4.1 Free-radical substitution from alkanes *(Refer to Alkane Lecture Notes for more details)*

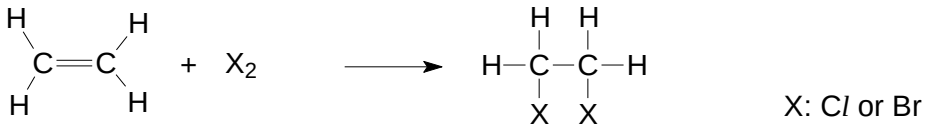
Type of reaction	Free-radical substitution
Reagents	Cl_2 (g) or Br_2 (*l*)
Condition	presence of ultraviolet (uv) light

Note:

- This is not a good method to prepare halogenoalkanes in the laboratory as it gives a mixture of products.
- It is difficult to control the extent and position of substitution.
- The use of a large excess of the alkane helps to give a better yield of the monosubstituted product.

4.2 Electrophilic addition from alkenes *(Refer to Alkene Lecture Notes for more details)*

4.2.1 Using X_2

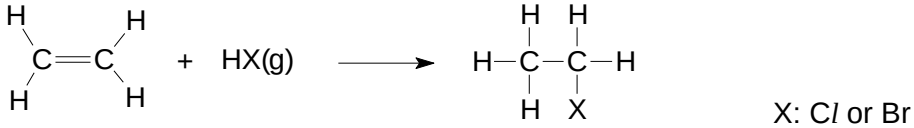


X: C*l* or Br

halogenoalkane

Type of reaction	Electrophilic addition
Reagent	$Br_2(l)$ or $Br_2(g)$ in CCl_4 / $Cl_2(g)$ in CCl_4
Condition	room temperature in the absence of light

4.2.2 Using HX



X: C*l* or Br

halogenoalkane

Type of reaction	Electrophilic addition
Reagent	gaseous HC*l*, HBr or HI
Condition	room temperature

Note:

- Markovnikov's rule applies for unsymmetrical alkenes.
- A mixture of products will be obtained.

4.3 Nucleophilic substitution from alcohols

	Reaction	Reagents and Conditions	Products
1	ROH + HX	Conc HC*l*, anhydrous $ZnCl_2$ catalyst, heat under reflux	R−C*l* + H_2O
		HBr(g) heat under reflux *(see **note (iv)** on in situ preparation of HX)*	R−Br + H_2O
2	ROH + PX_3	Anhydrous $PCl_3(l)$, r.t.	R−C*l* + H_3PO_3
		Anhydrous $PBr_3(l)$, r.t. *(see **note (v)** in situ preparation of PBr_3)*	R−Br + H_3PO_3
		(red) P + I_2(s), heat under reflux	R−I + H_3PO_3
3	ROH + PCl_5	Anhydrous PCl_5(s), r.t.	R−C*l* + $POCl_3$ + HC*l*
4	ROH + $SOCl_2$	Anhydrous $SOCl_2(l)$, r.t.	R−C*l* + SO_2 + HC*l*

Type of reaction	Nucleophilic substitution
Observations	For reaction of alcohol with PCl_5 and $SOCl_2$, **steamy white fumes of HC*l*** are produced, which turn **damp blue litmus paper red.**

Examples

1) $CH_3CH_2OH + HBr(g) \xrightarrow[\text{under reflux}]{\text{heat}} CH_3CH_2Br + H_2O$

2) $CH_3CH_2OH + PCl_5\text{ (anhydrous)} \xrightarrow{\text{r.t.}} CH_3CH_2Cl + POCl_3 + HCl$

3) $CH_3CH_2OH + SOCl_2\text{ (anhydrous)} \xrightarrow{\text{r.t.}} CH_3CH_2Cl + SO_2 + HCl$

Note:

(i) Reactions with PCl_5 and $SOCl_2$ are useful in determining the presence of hydroxyl groups. However, the same observations will be seen if **carboxylic acids** are present.

(ii) When using PCl_3, PCl_5 and $SOCl_2$, ensure that there is **absence** of water (anhydrous condition). This is because these compounds react with water to give other products:
$PCl_3(l) + 3\,H_2O(l) \rightarrow H_3PO_3(aq) + 3\,HCl(aq)$
$PCl_5(s) + 4\,H_2O(l) \rightarrow H_3PO_4(aq) + 5\,HCl(aq)$
$SOCl_2(l) + H_2O(l) \rightarrow SO_2(g) + 2\,HCl(g)$

(iii) The advantage of using $SOCl_2$, is that the two by−products are both gases (SO_2 and HC*l*), so they separate themselves from the required liquid RC*l* product easily. Excess $SOCl_2$ (b.p. 79ºC) can also be removed by distillation.
(Note: chloromethane and chloroethane are gases at room temperature)

(iv) HBr(g) may be prepared *in situ* by reacting solid NaBr with concentrated H_2SO_4 and heat. (*in situ*: Latin phrase, typically means "in the reaction mixture")
$NaBr + H_2SO_4 \rightarrow HBr + NaHSO_4$

(v) PBr_3 or PI_3, is prepared *in situ* by heating red phosphorus with liquid bromine or solid iodine respectively.
$2P + 3\ X_2 \rightarrow 2PX_3$ X = Br, I

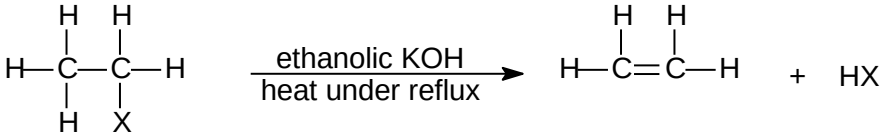
5 CHEMICAL REACTIONS OF HALOGENOALKANES

What types of reactions do halogenoalkanes undergo and why?
Which classes of reagents do halogenoalkanes react with and why?

Halogenoalkanes undergo two types of reactions:
- Elimination – *elimination of HX to form alkenes*
- Nucleophilic substitution – *substitution of halogen atom by nucleophiles*

5.1 Elimination

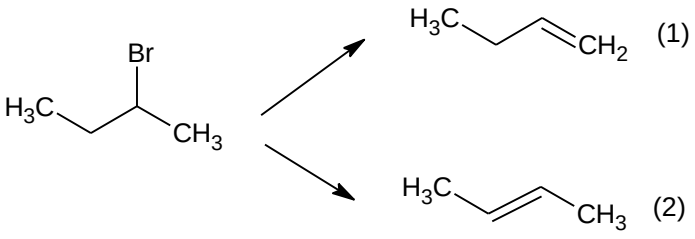
Formation of alkenes



Type of reaction	Elimination
Reagent	KOH (or NaOH) in ethanol
Condition	Heat under reflux

Note:
Elimination of unsymmetrical halogenoalkanes may give more than one alkene. Saytzeff's Rule is applied to determine which is the major product (the more substituted alkene).

Checkpoint 4
Which is the more likely product when 2−bromobutane undergoes elimination reaction with alcoholic KOH?



5.2 Nucleophilic Substitution

- The chemical reactivity of halogenoalkanes is due to its polarised C−X bond: $C^{\delta+} - X^{\delta-}$
- The **<u>electron−deficient</u>** $C^{\delta+}$ atom in R−X is susceptible to attack by **<u>nucleophiles</u>**.

$$Nu:^- \quad + \quad R{-}X \longrightarrow R{-}Nu \quad + \quad X^-$$

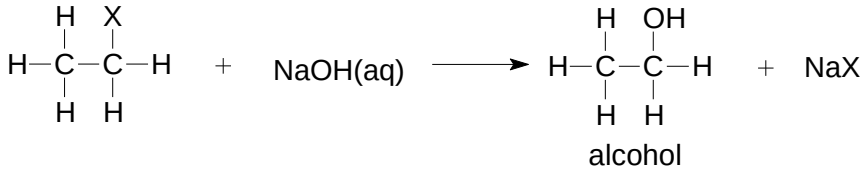
- Recall: A **nucleophile** is an **<u>electron−rich species</u>** and it forms a **dative bond** by donating an electron pair to an electron−poor site.

- Possible nucleophiles:
  - **anions** such as OH^-, CN^-, CH_3COO^-, $CH_3CH_2O^-$
  - **neutral molecules** with **lone pairs of electrons** such as H_2O, NH_3
- Halide ion, X^-, is a **good leaving group**[1] due to its stability as an extremely **weak (Lewis) base**[2]**.**

[1] *In chemistry, a **leaving group** is a molecular fragment that departs with a pair of electrons in heterolytic bond cleavage. Leaving groups can be anions or neutral molecules, but in either case it is crucial that the leaving group is able to stabilise the additional electron density that results from bond heterolysis (heterolytic fission).*

[2] *A Lewis base is an electron-pair donor. X^- is a weak Lewis base as it is stable and does not readily donate away its electron pairs.*

5.2.1 Formation of alcohols (hydrolysis)

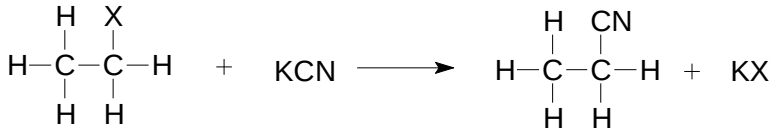


alcohol

Type of reaction	Nucleophilic substitution
Reagent	KOH (aq) or NaOH (aq)
Condition	Heat under reflux

Note:
- The reagent (NaOH or KOH) is the same in elimination and substitution reactions.
- Only the **<u>solvent</u>** used affects the type of reaction undergone:
  - **Aqueous** solution: **Nucleophilic substitution**
  - **<u>E</u>thanolic** solution: **<u>E</u>limination** (OH^- in ethanolic medium behaves as a strong base)

5.2.2 Formation of nitriles



nitrile

Type of reaction	Nucleophilic substitution
Reagent	KCN in ethanol (or ethanolic KCN)
Condition	Heat under reflux

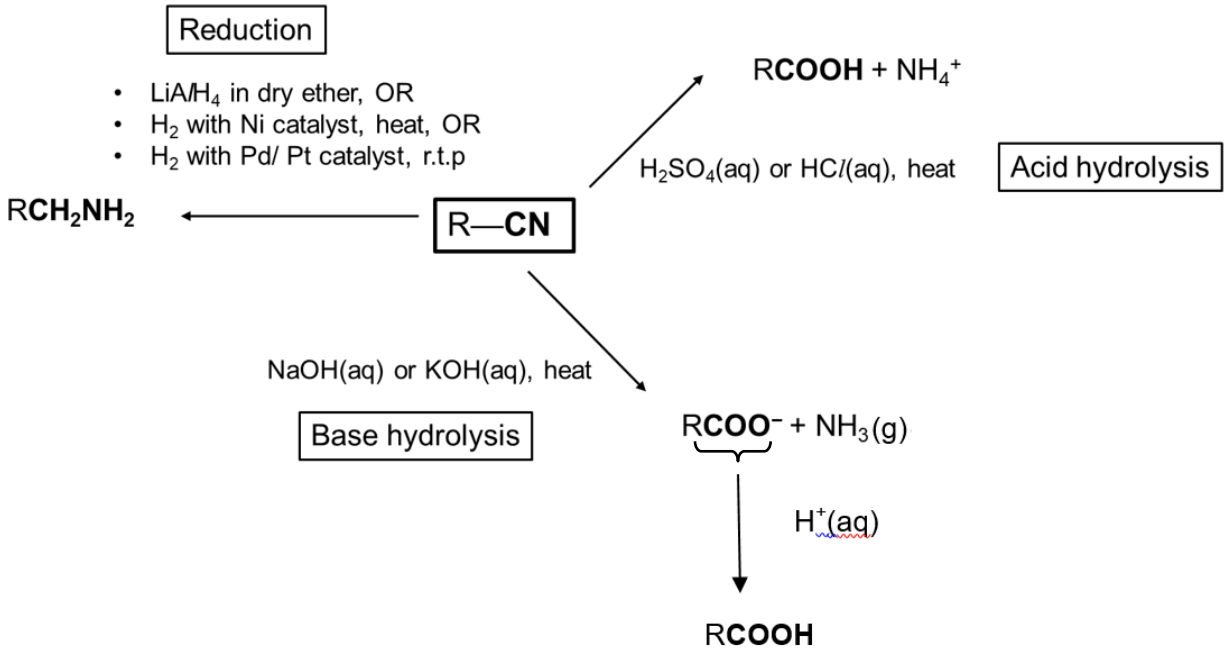
Note:

- The reaction is useful in organic synthesis it is a good method to **increase the length of a carbon chain** by **<u>one carbon</u>** atom (a step−up reaction)

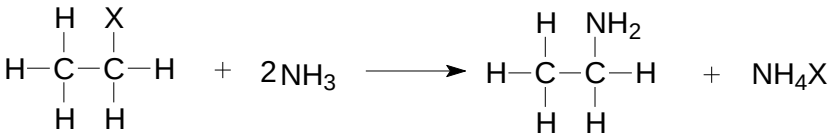
- Nitriles (RCN) formed can be further converted to carboxylic acids (RCOOH), salts of carboxylic acid ($RCOO^-$) and primary amine (RCH_2NH_2) as shown below.

Type of reaction	**Equation**	**Reagents and conditions**
Acid hydrolysis	R—**CN** + $2H_2O$ + H^+ ⟶ R**COOH** + NH_4^+	H_2SO_4(aq) or HC*l*(aq), Heat
Base hydrolysis	R—**CN** + H_2O + OH^- ⟶ R**COO**$^-$ + NH_3 Further acidification R**COO**$^-$ + H^+ ⟶ R**COOH**	NaOH(aq) or KOH(aq) heat, followed by H_2SO_4(aq), r.t.p
Reduction	R—**CN** + 4[H] ⟶ R**CH_2NH_2** *(1)* R—**CN** + $2H_2$ ⟶ R**CH_2NH_2** *(2 & 3)*	(1) Li*A*lH_4 in dry ether, r.t.p ($NaBH_4$ <u>cannot</u> be used) (2) H_2 with Ni catalyst, heat (3) H_2 with Pd/ Pt catalyst, r.t.p

Summary



5.2.3 Formation of primary amines (Ammonolysis)

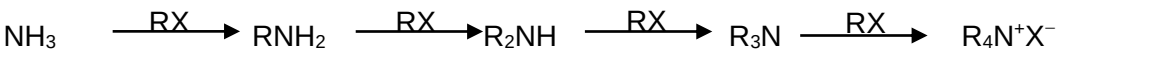


primary amine

Type of reaction	Nucleophilic substitution
Reagent	Excess concentrated NH_3 in ethanol
Condition	Heat in a sealed tube

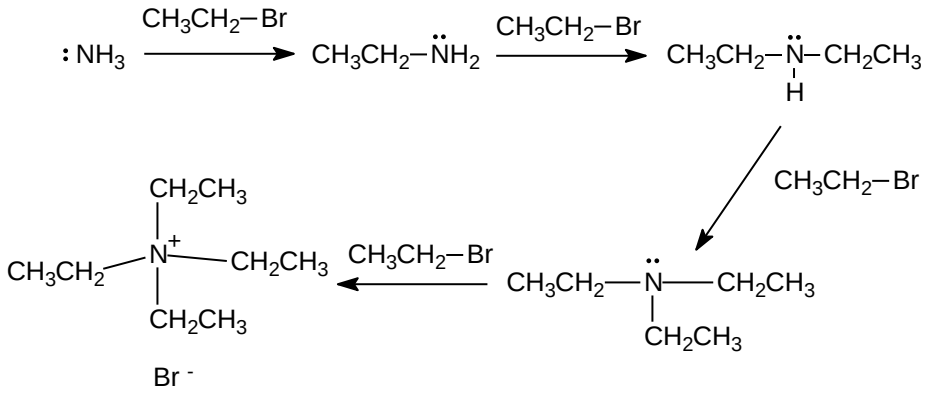
Note:
If **RX were in excess**, multiple substitutions could occur, forming a mixture of **1°, 2° and 3° amines** and a **quaternary ammonium salt**.

Reaction between **excess RX** and NH_3:



1° amine **2° amine** **3° amine** **quaternary ammonium salt**

Example
Reaction between **excess CH_3CH_2Br** and NH_3:

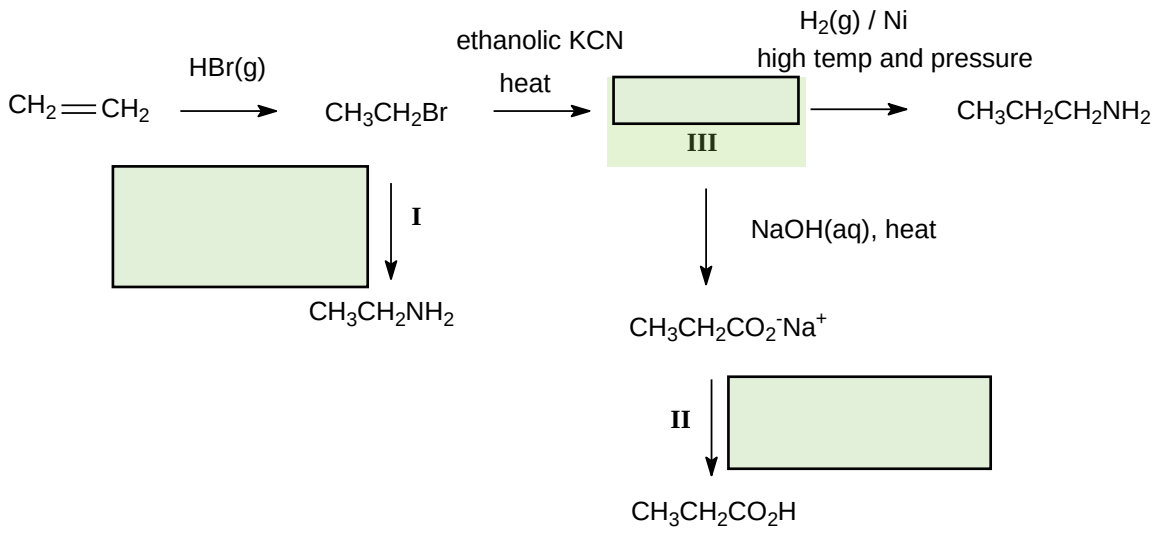


Reason:
RNH_2 formed possesses **a lone pair of electrons on the N atom**, thus acting as a **nucleophile** to attack the **excess RX** present via further nucleophilic substitutions.

(The electron donating effect of alkyl group(s) on amine make(s) the amine more nucleophilic than ammonia.)

Checkpoint 5

Complete the following flowchart with the appropriate reagents and conditions for **I** and **II**, and draw the organic product **III**.



5.3 Nucleophilic Substitution Mechanism

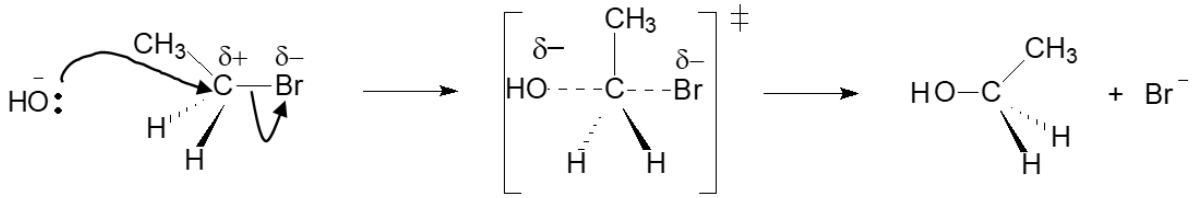
How do halogenalkanes react with nucleophiles?
What are the factors that determine the mechanism of nucleophilic substitution?

Nucleophilic substitution reaction can occur via 2 different mechanisms:

- **S_N2: Bimolecular nucleophilic substitution mechanism**
- **S_N1: Unimolecular nucleophilic substitution mechanism**

5.3.1 S_N2 (Bimolecular nucleophilic substitution mechanism)

- A **one−step** mechanism (**without intermediates!**)
- The following illustrates the mechanism of the nucleophilic substitution reaction (**hydrolysis)** of a **primary** alkyl halide, CH_3CH_2Br with OH^-



Nucleophile, OH^-, uses its lone−pair of electrons to attack the electron−deficient carbon 180° away (i.e. *attack from the back*) from the departing halogen atom, Br.

This forms a pentavalent **transition state** (not a reaction intermediate which can exist independently) with a partially formed C−OH bond and a partially broken C−Br bond.

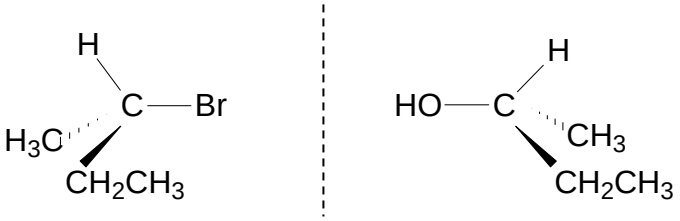
The C−OH bond fully forms.

Br^- ion departs as leaving group.

Inversion of stereochemistry

Stereochemistry[3] of S_N2 reaction

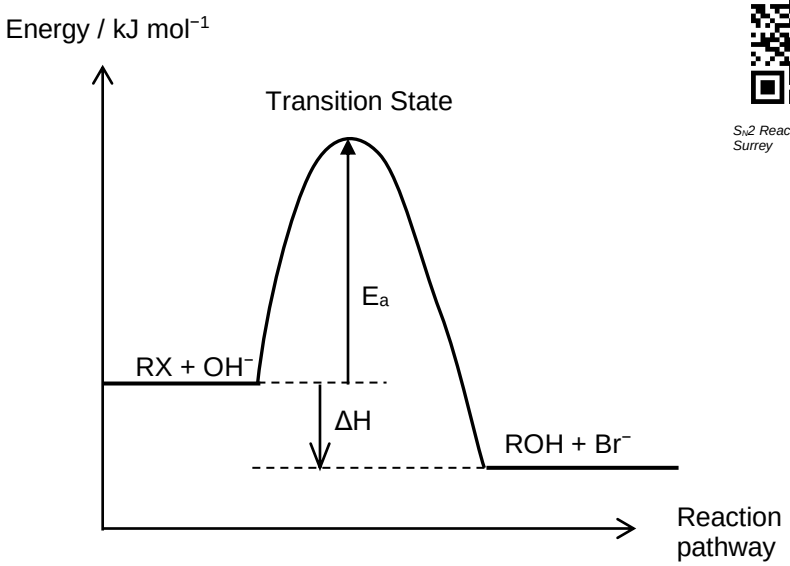
E.g. When a **chiral** compound, 2−bromobutane, reacts with aqueous hydroxide ions (OH^-) via an **S_N2 mechanism** (when nucleophile *attacks from the back*), the stereochemistry at the δ+ carbon is **inverted** (or inversion of configuration*) as C−Nu bond forms fully.



Reactant **Product**

** where the product's configuration is opposite that of the reactant*

Energy profile diagram of S_N2 reaction



S_N2 Reactions | University Of Surrey

Checkpoint 6

Why is there only 1 activation energy observed in the energy profile diagram?

The number of activation energy observed is dependent on the number of steps involved in the reaction. Since a S_N2 reaction involves **a _____ mechanism**, there is only one activation energy observed.

Characteristics of S_N2 mechanism:

- Rate equation: **rate = *k* [RX] [Nu]** (**bi**molecular)
- Reactivity of halogenoalkanes (RX) in S_N2 reactions:

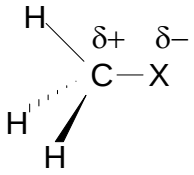
(slowest) 3^o < 2^o < **1^o** < **CH_3X** **(fastest)**

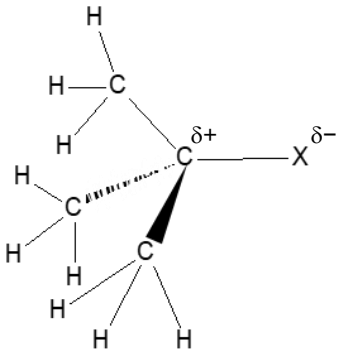
Reasons for the order of reactivity

1. **Steric hindrance**
   The more R (alkyl) groups attached to the C atom bearing the X atom, the **more crowded** at the electrophilic C centre ($^{\delta+}$C), the more difficult for the nucleophile to approach it.

2. **Weak electrophilic C centre ($^{\delta+}$C)**
   The more electron-donating R (alkyl) groups attached to the C atom bearing the X atom, the **less electron deficient** is the electrophilic C centre ($^{\delta+}$C), hence less attractive to the attacking nucleophile.

   E.g.:

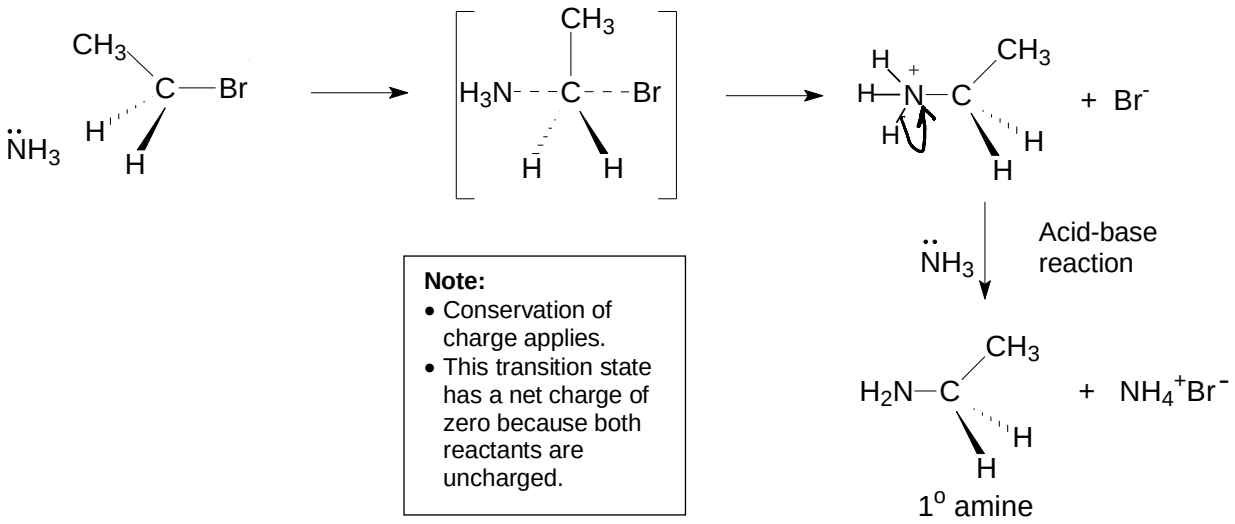
Nu: 

Nu: 

Checkpoint 7

Describe the mechanism for the reaction of bromoethane with excess concentrated ammonia in ethanol heat in sealed tube.

Name of mechanism: _____ (**S_N2**)

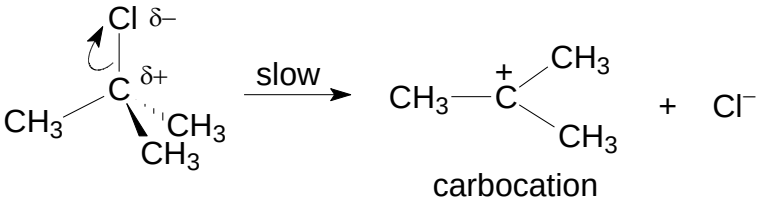


Note:
- Conservation of charge applies.
- This transition state has a net charge of zero because both reactants are uncharged.

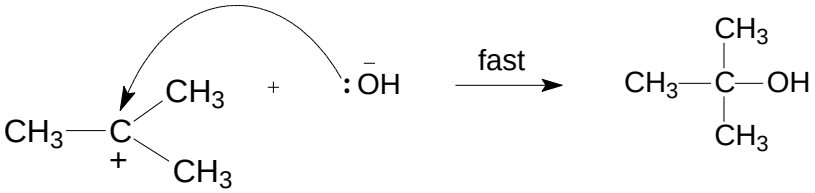
5.3.2 S_N1 (Unimolecular nucleophilic substitution mechanism)

- A **<u>two−step</u>** mechanism **forming carbocation intermediate**
- The following illustrates the mechanism of the **hydrolysis** of a **<u>tertiary</u>** alkyl halide, $C(CH_3)_3Cl$

Step 1: **<u>Heterolytic fission</u>** of the C−C*l* bond gives a carbocation intermediate and a chloride ion. This is the **<u>rate−determining step.</u>**



Step 2: The carbocation is very **<u>reactive</u>** and is readily attacked by the nucleophile, OH^-.

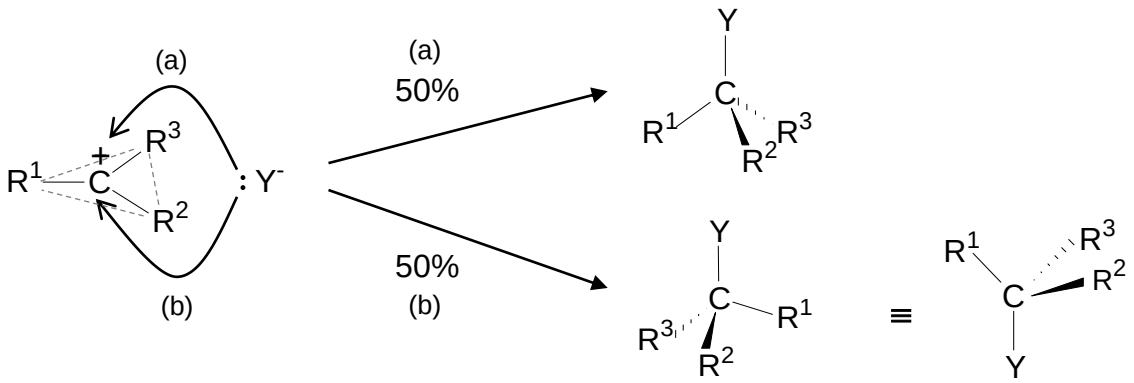


<u>Stereochemistry of S_N1 reaction</u>

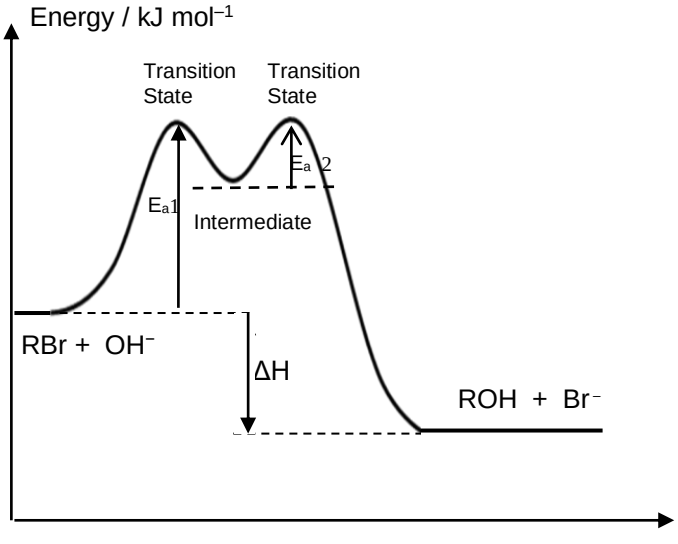
If the halogenoalkane has a chiral carbon, a **<u>racemic</u>** mixture is formed.

<u>Reason</u>:
Since the carbocation intermediate has a **<u>trigonal planar</u>** structure, the nucleophile attacks from either side of the plane with **<u>equal probabilities</u>**, yielding **<u>equal quantities of both enantiomers</u>**. Thus, a **<u>racemic mixture</u>** is formed.

(*Recall*: A racemic mixture is <u>optically inactive</u>, i.e. is unable to rotate plane−polarised light.)



Energy profile diagram of S_N1 reaction



SN1 Reactions | University Of Surrey

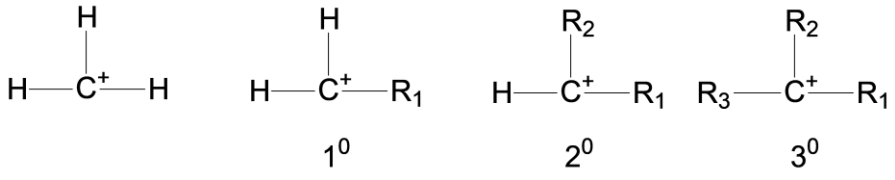
Characteristics of S_N1 mechanism

- Rate equation: **rate = *k* [RX]** (**uni**molecular rate−determining step)
- Reactivity of halogenoalkanes in S_N1 reactions:

  (slowest) CH_3X < 1° < 2° **< 3° (fastest)**

  Reason
  In step 1, a carbocation intermediate is formed. A 3° RX forms a **3°** carbocation intermediate. Since there are **more electron donating alkyl groups** bonded to C+, the **positive charge is dispersed to a greater extent**. Hence, a **more stable carbocation intermediate** is formed.

  Therefore, the stability of carbocation increases with increasing alkyl substitution. The **relative stability of carbocation** is as shown below:



(least stable) methyl carbocation < 1° carbocation < 2° carbocation < 3° carbocation (most stable)

5.3.3 Summary (S_N2 vs S_N1)

	S_N2 mechanism	**S_N1 mechanism**
No. of steps in mechanism	A single−step mechanism	A two−step mechanism
Rate equation	**rate = *k* [RX] [Nu]**	**rate = *k* [RX]**
Reactivity	Fastest: 1^o halogenoalkanes (least steric hindrance)	Fastest: 3^o halogenoalkanes (most stable carbocation intermediate formed)
Stereochemistry of product if RX has a chiral carbon	Inversion of configuration of product	Racemic mixture formed

Note:

One important factor that determines which mechanism **predominates** (or proceeds faster) is the **classification** of the halogenoalkane. 1^o halogenoalkanes usually undergo S_N2 mechanism whilst 3^o halogenoalkanes usually undergo S_N1 mechanism.

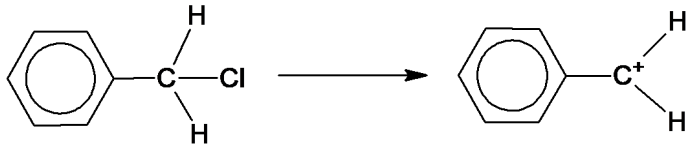
The type of mechanism adopted by 2^o halogenoalkane is dependent on the proposed rate equation.

Examples of exceptions:

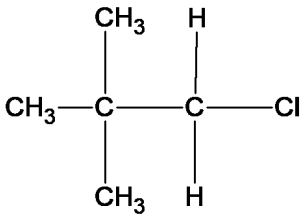
1. Suggest why (chloromethyl)benzene, being a primary halide, favours substitution by the S_N1 mechanism.

   Reason

   The benzyl carbocation is stable due to the delocalisation of the positive charge into the benzene ring.



2. Suggest why 1−chloro−2,2−dimethylpropane, $(CH_3)_3CCH_2Cl$ is inert to S_N2 mechanism.



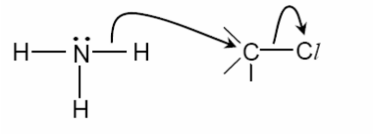
   Reason

   Despite being a primary alkyl halide with only 1 alkyl group on the electrophilic C centre ($^{\delta+}$C), the attack of the nucleophile is blocked (hindered) by the large alkyl group present. This creates significant steric hindrance in the substitution via S_N2 mechanism.

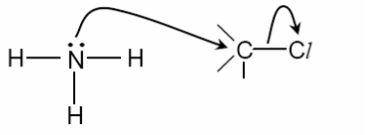
Checkpoint 8

1. Which diagram correctly shows the movement of electrons when ammonia reacts with a chloroalkane?

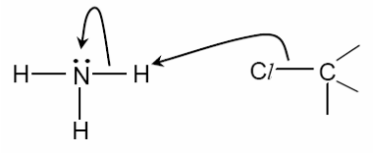
A



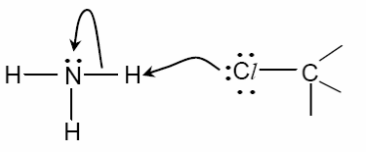
B



C

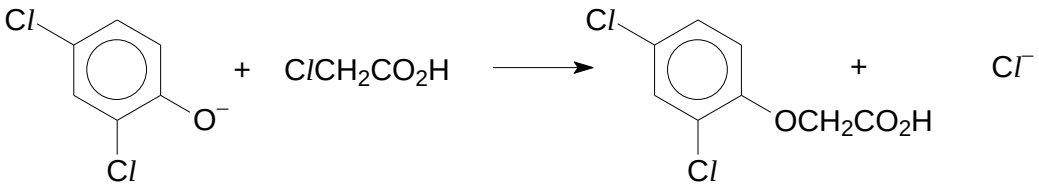


D



Answer: __

2. The weed killer 2,4–D may be synthesised in the laboratory by the following reaction.



2,4–D

What is the mechanism of this reaction?

A electrophilic addition

B electrophilic substitution

C elimination

D nucleophilic substitution

Hint
- Identify the **reactive carbon.**
- Is the carbon atom **electron−rich** or **electron deficient**?

Answer: ____

5.4 Reactivity among different alkyl halides in Nucleophilic Substitution Reactions

Nucleophilic substitution of halogenoalkanes involves breaking the C−X bond to form X^-.

Hence, the **weaker** the C−X bond and the **greater the stability** of the X^- formed, the **more reactive** is the halogenoalkane.

5.4.1 Factors affecting reactivity among halogenoalkanes

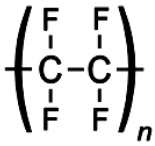
(a) Strength of C–X bond

Bond	C–F	C–C*l*	C–Br	C–I
Bond energy/ kJ mol^{-1}	485	340	280	240

From the *Data Booklet*, bond energy of C–X bond decreases for F to I.
⇒ ease of breaking C–X bond increases
⇒ formation of X^- will be faster

Hence, the order of reactivity: RI > RBr > RC*l* > RF

This explains the inertness of fluoro compounds; hence the use of Teflon (polytetrafluoroethylene) in cookwares.



(b) Stability of the leaving group, X^-

Good leaving groups are weak (Lewis) bases. *(see note 2 on page 10)*

	H–F	H–C*l*	H–Br	H–I
pK_a (HX)	+3	−7	−9	−10
*K_a (HX)	10^{-3}	10^{7}	10^{9}	10^{10}
*K_b (X^-)	10^{-11}	10^{-21}	10^{-23}	10^{-24}

*K_a (acid dissociation constant) and *K_b (base dissociation constant) is a measure of the strength of an acid and a base, respectively. [This concept has been covered in greater details in Acid−base Equilibria.]

Weak (Lewis) bases have low K_b values. From the table, the I^- formed has the lowest K_b value, so it is a weakest electron pair donor. Hence, it is most stable and most unreactive, and thus a best leaving group.

Hence, the stability of halide ion (leaving group): **I^- > Br^- > Cl^- > F^-** resulting in
the order of reactivity: RI > RBr > RC*l* > RF

Summary

- Both the C−X bond energy and K_b value suggest that iodide is the best leaving group, while fluoride is the worst.
- Hence, alkyl iodide is the most reactive towards nucleophilic substitution, while alkyl fluoride is the least.

Checkpoint 9

Why does the reaction $C_2H_5X + OH^- \longrightarrow C_2H_5OH + X^-$ take place more rapidly in aqueous solution when X is I than when X is Br?

A The I^- ion is a stronger nucleophile than the Br^- ion.

B The I^- ion is less hydrated in solution than the Br^- ion.

C The C–Br bond is more polar than the C–I bond.

D The C–Br bond is stronger than the C–I bond.

Answer: ____

5.4.2 Can the polarity of C–X bond account for the reactivity of halogenolkanes in nucleophilic substitution reactions?

Polarity of C-X bond

Element	C	F	Cl	Br	I
Electronegativity value	2.5	4.0	3.0	2.8	2.5

- C−X bond is polar: $C^{\delta+} - X^{\delta-}$
- The greater the difference in electronegativity between C and X, the greater the polarity of the C–X bond. This makes the C more electron deficient and hence it is more susceptible to an attack by nucleophiles.
- Thus, polarity of the C–X bond alone would predict that fluoro–compounds would be the most reactive.

However, based on the strength of C–X bond alone (see 5.4.1(a)), the iodo-compounds would be the most reactivity.

The two factors are in opposition.

From experimental results, iodo-compounds have the fastest rate of reaction. Hence **strength of the C–X bond is a more significant factor** that governs the reaction rate as compared to polarity of C–X bond.

6. USES OF HALOGENOALKANES

Bond	C–F	C–C*l*	C–Br	C–I
Bond energy/ kJ mol^{-1}	485	340	280	240

- C−F bond is very strong.
- Fluoroalkanes and fluorohalogenoalkanes are hence chemically inert.
- Some important uses of halogenoalkanes:

Uses	**Compounds**	**Comments**
solvent	CCl_4 CH_2Cl_2 $CCl_2{=}CHCl$ $CCl_2{=}CCl_2$ $CCl_2F–CClF_2$	– good solvents for non–polar substances (e.g. oil, grease)
refrigerant fluid	CCl_2F_2 $CFCl_3$ $CF_2ClCFCl_2$	– gas will liquefy when compressed under pressure, then sudden expansion leads to vaporisation which removes heat from the surrounding, giving a cooling effect
aerosol propellant	CCl_2F_2 $CFCl_3$ $CF_2ClCFCl_2$	– dissolves chemicals found in paint/ hair spray/ insecticides and keep them in solution in pressurised container – a liquid under pressure in the aerosol can. When valve opens, some vaporises, carries with it the active components
fire extinguisher	CBr_2ClF $CClBrF_2$	– relatively inert to combustion (due to absence of H atoms) – heavy (due to presence of Br atoms) which makes it easy to settle down and cut off oxygen supply
anesthetic	$CF_3CHBrCl$ (Halothane)	– non–toxic – non–flammable – no apparent side–effects
monomer for plastic	$CH_2{=}CHCl$ $CF_2{=}CF_2$	– e.g. PVC used for clothing packaging, pipes – e.g. Teflon used for non–stick property in frying pans

7. CFCS AND THE OZONE LAYER

when CFCs meet Ozone

Chlorofluorocarbons (CFCs) are halogenoalkanes containing C, C*l* and F atoms and no H atoms. E.g. CCl_3F, CCl_2F_2, $C_2Cl_2F_4$, $CCl_2F–CClF_2$.

In the past, CFCs were used widely as refrigerants and aerosol propellants. This is because they are unreactive/inert, non−flammable, non−toxic, odourless and easily liquefied by a little pressure above atmospheric pressure.

Damage to the stratospheric ozone layer

- Due to the strength of C–F and C–C*l* bonds, fluoroalkanes and chlorofluoroalkanes (CFCs) are stable molecular entities under ambient conditions, which exhibit **low toxicity**, **low reactivity** and **low flammability**.
- CFCs are insoluble in water and so unreactive that they can remain in the atmosphere for many years without breaking down.
- However, this lack of reactivity also provides fluorochloroalknes with a lifespan that can exceed 100 years, giving them time to diffuse into the upper stratosphere.
- At the stratosphere, the presence of the high energy UV radiation results in homolytic fission of the C–C*l* bond to yield reactive chlorine radicals.
- These radicals initiate the chain reaction of the destruction of the ozone molecules.
- This upsets the equilibrium between ozone formation and ozone breakdown.

Mechanism (not required)

1. Ozone formation:

$$O_2 \longrightarrow 2\,O$$
$$O + O_2 \longrightarrow O_3 \text{ (ozone)}$$

2. When C*l*• radicals are present, ozone is removed and the C*l*• radicals are regenerated.

$$O_3 + Cl\bullet \longrightarrow O_2 + ClO\bullet$$
$$ClO\bullet + O \longrightarrow Cl\bullet + O_2$$

Thus, the C*l*• radicals act as catalysts which result in continuous destruction of the ozone molecules.

Alternatives to CFCs:

- Nitrogen, carbon dioxide or liquefied petroleum gases (e.g. propane) as aerosol propellants.
- Hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs)

  These halogenoalkanes are not fully halogenated. The presence of hydrogen atom(s) makes these compounds less stable than CFCs. Hence, they do not reach the stratosphere in large concentrations.

  1. Hydrofluorocarbons, HFCs (e.g. CF_3CH_2F, CH_2FCF_3)
     - Do not contain C*l* atoms and thus do not release C*l*• in the stratosphere.
     - Contain at least one hydrogen atom and thus the C–H bond can be attacked by HO• radicals in the lower atmosphere. HO• radicals are produced by the reaction of an excited oxygen atom with water in the atmosphere

$$O\bullet + H_2O \longrightarrow 2\,HO\bullet$$

  2. Hydrochlorofluorocarbons, HCFCs (e.g. $CHCl_2CF_3$, $CHClF_2$, $C_2H_3Cl_2F$)
     - Contain at least one hydrogen atom and thus the C–H bond can be attacked by HO• radicals in the lower atmosphere.

(II) HALOGENOARENE

8. PREPARATION OF HALOGENOARENE

How are halogenoarenes synthesised?

8.1 Electrophilic substitution from benzene *(Refer to Arene Lecture Notes for more details)*

X= C*l* or Br

Type of reaction	Electrophilic substitution
Reagent	X_2 (where X_2 = C*l*$_2$ (g) or Br_2 (*l*))
Condition	Fe(s) or FeX_3(s) or A*l*X_3(s) Room temperature, anhydrous *(When Fe catalyst is used, must write equation: $2Fe + 3X_2 \rightarrow 2FeX_3$)*

9 CHEMICAL REACTIVITY AND REACTIONS OF HALOGENOARENE

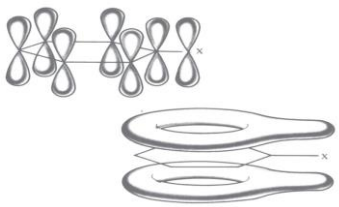
9.1 Reactivity towards nucleophilic substitution

Halogenoarenes are very much **less susceptible to nucleophilic substitution** than halogenoalkanes. Nucleophilic substitution is only possible under very vigorous conditions.

<u>Reasons for non-reactivity towards nucleophilic substitution</u>

(i) Delocalisation of lone pair of electrons on halogen

- The p−orbital of the X atom in C_6H_5X **overlaps** with the π electron cloud of the benzene ring.



- The lone pair of electrons on the X atom can **delocalise** into the benzene ring. This results in:
  - **<u>Partial double bond to the C-X bond.</u>** C-X bond is stronger and more difficult to cleave.
  - **<u>Reduced partial positive charge on C of C–X bond.</u>** C is less susceptible to attack by nucleophiles

(ii) Steric hindrance

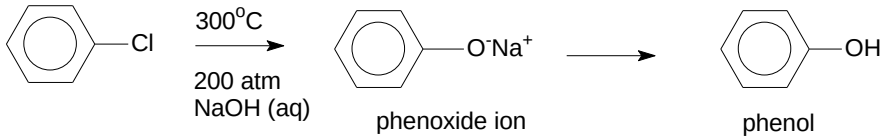
- The rear side of the C−X bond in halogenoarenes is blocked by the benzene ring.
- The π−electron cloud of the benzene ring will repel the lone pair of electrons of the incoming nucleophile, making it difficult for the nucleophile to approach.

(iii) Hybridisation state of the C

- The sp^2 hybridised carbon in the C–X bond of halogenoarenes contains more *s*−character than the sp^3 hybridised carbon in the C–X bond of halogenoalkanes.
  - ➢ the bonding electrons in the C-X bond are held more closely to the nucleus
  - ➢ the sp^2−C−X bonds in halogenoarenes are stronger and more difficult to cleave.

Hence halogenoarenes undergo nucleophilic substitution reactions only under **very drastic** and **vigorous** conditions such as **high temperature and pressure**.

Industrial application (FYI)



9.2 Reactivity towards elimination

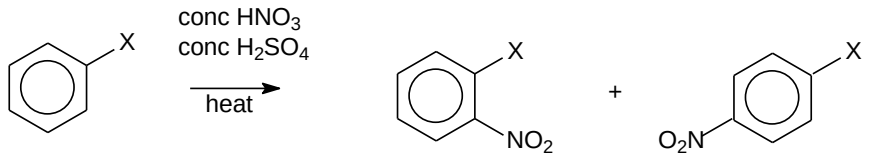
Halogenoarenes **DO NOT** undergo Elimination reactions as this would **disrupt the stable delocalised π electron system** of the benzene ring, which would require a large amount of energy.

9.3 Electrophilic substitution

- Halogenoarenes undergo **<u>electrophilic substitution</u>** reactions involving benzene ring just like any other arenes.

- However, halogenoarenes are much less susceptible to electrophilic substitution as the **halogen substituent is deactivating**. The halogen substituent is also 2,4−directing.

- The deactivating and directing effects are seen in the nitration of chlorobenzene where a higher temperature is required and two isomers are formed.



X = C*l*, Br, I

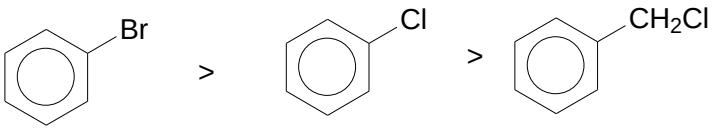
Checkpoint 10

Which sequence shows the correct order of **decreasing** ease of hydrolysis?

A $CH_3CH_2Cl > CH_3CH_2Br > CH_3CH_2I$

B $(CH_3)_2CHCl > (CH_3)_2CHI > (CH_3)_2CHBr$

C



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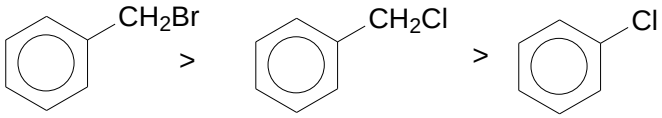


Answer: ____

Explanation:

- Bond energy of C—Br in $C_6H_5CH_2Br$ is _____ than that of C—C*l* in $C_6H_5CH_2Cl$, hence C—Br bond breaks _____ easily
- C—C*l* in C_6H_5Cl is _____ strong (refer to Section 9.1)

10 CHEMICAL TEST FOR HALOGENOALKANES

10.1 Comparing colour of silver halide (AgX) ppt

- The general method for distinguishing between the type of halogen substituents present in halogenoalkanes is to compare the colour of the silver halide precipitates that are formed after the compound undergoes nucleophilic substitution by hydroxide ion. The test involves 3 steps.

Step 1: Add **NaOH(aq)** and heat.

$$R{-}X + OH^- \longrightarrow R{-}OH + X^-$$

[Breaking of the C−X bond]

Step 2: **Cool** the mixture and then add **excess dilute HNO_3**.
[To neutralise any excess NaOH(aq) to prevent the formation of Ag_2O]

Step 3: Add **$AgNO_3$(aq)** and observe the **colour** of precipitate formed.

$$Ag^+(aq) + X^-(aq) \longrightarrow AgX(s)$$

[Detect the presence of X^-]

******FYI*: $2Ag^+ + 2\,OH^- \rightarrow Ag_2O + H_2O$**

- The expected observations (for the positive tests) are given in the table below. Sometimes, the colours of AgC*l* and AgBr are difficult to differentiate.

- We can follow up by adding NH_3(aq); AgC*l* dissolves in dilute aqueous NH_3 while AgBr does not.

	Chloroalkane, RC*l*	**Bromoalkane, RBr**	**Iodoalkane, RI**
Colour of precipitate formed	white	pale cream	yellow
Identity of precipitate	AgC*l*	AgBr	AgI
Solubility of precipitate in NH_3 solution	dissolves in dilute aqueous NH_3	Insoluble in aqueous NH_3 Dissolves in concentrated NH_3	Insoluble even in concentrated NH_3
	Reaction: $AgX(s) + 2NH_3 \rightarrow [Ag(NH_3)_2]^+(aq) + X^-(aq)$ colourless complex ion *Refer to Solubility Equilibria lecture notes for the explanation on the solubility off AgX in aqueous ammonia.*		

10.2 Comparing rate of formation of AgX ppt

- In this method, the rates of the formation of the silver halide precipitates are used to distinguish between the different halogens in the halogenoalkanes.

  - Alkyl halides undergo <u>hydrolysis / nucleophilic substitution</u>, releasing X^- ion.

  - The X^- ion released forms a ppt with Ag^+ from $AgNO_3$(aq):

$$Ag^+ + X^- \longrightarrow AgX(s)$$

	Chloroalkane, RC*l*	**Bromoalkane, RBr**	**Iodoalkane , RI**
Add 1 cm^3 of the organic compound in a test tube. **Add 1 cm^3 of ethanolic $AgNO_3$ and place the test tube in a hot water bath.** ***(Nucleophile: CH_3CH_2OH)***	white ppt (AgC*l*) formed in 5−8 min	pale cream ppt. (AgBr) formed in 3−5 min	yellow ppt (AgI) formed almost immediately

Note: Similar reaction can take place with aqueous $AgNO_3$. The nucleophile involved will be H_2O.

<u>Explanation for the difference in the rate of formation of AgX precipitate</u>

- The **rate** at which the silver halide precipitate is formed is determined by the **strength of the C−X bond**.

Bond	C–C*l*	C–Br	C–I
Bond energy/ kJ mol^{-1}	340	280	240

- Since C–X <u>bond energy decreases</u> from C–C*l* to C–Br to C–I, the ease at which these bonds break increases in this order and the <u>rate of formation of halide ions</u> increases in this order.

- Hence, AgI precipitate forms most quickly, followed by AgBr, and AgC*l* is formed the slowest.

A precipitate is <u>not</u> formed when **halogenoarenes and fluoroalkanes** undergo the described chemical test:

1. RF: Contains **a very strong C−F bond** which is very difficult to break.

2. Halogenoarenes: p–orbital of the X atom overlaps with the π–electron cloud of the benzene ring. The <u>lone pair of electrons</u> of the <u>X atom</u> can <u>delocalise</u> into the benzene ring creating partial <u>double bond character</u>, resulting in the <u>stronger</u> C–X bond.

Hence nucleophilic substitution cannot take place and no ppt is formed.

Checkpoint 11:

For the following pairs of compounds, describe one simple chemical test to distinguish between them. State clearly how **each** compound behaves in the test.

(a) CH_3CH_2I and CH_3CH_2Cl

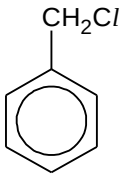
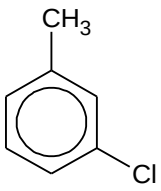
Step 1: _____ each compound in a test−tube with aqueous _____

Step 2: _____. Acidify resulting mixture with dilute _____to remove excess NaOH

Step 3: Add aqueous $AgNO_3$ to the mixture

CH_3CH_2Cl : _____ ppt formed.

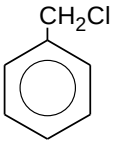
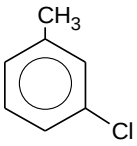
CH_3CH_2I : _____ ppt formed.

(b)  and 

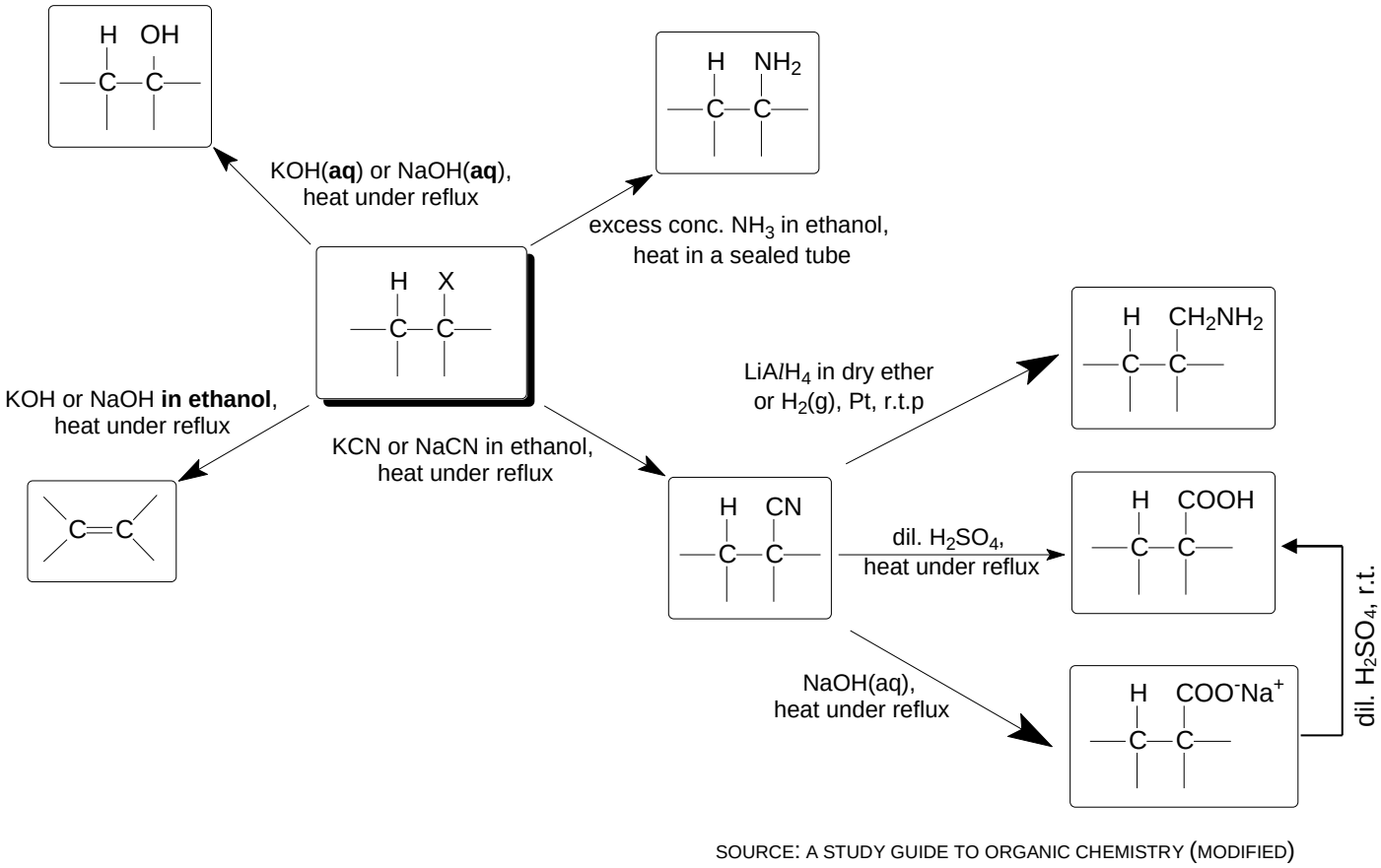
Step 1: Heat each compound in a test−tube with aqueous NaOH

Step 2: Cool. Acidify resulting mixture with dilute HNO_3 to remove excess NaOH

Step 3: Add aqueous $AgNO_3$ to the mixture

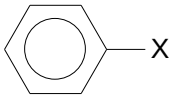
 _____ ppt formed ;  _____ ppt formed

SUMMARY: REACTIONS OF HALOGENOALKANES (ALKYL HALIDES)

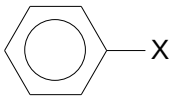


SOURCE: A STUDY GUIDE TO ORGANIC CHEMISTRY (MODIFIED)

HALOGENOARENES (ARYL HALIDES)



KOH(**aq**) or NaOH(**aq**), heat under reflux → **no reaction**



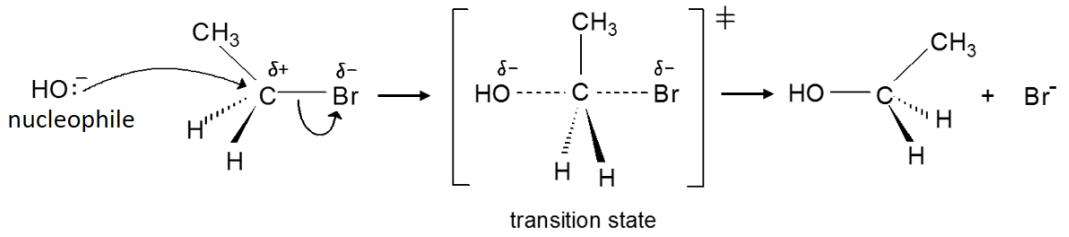
KOH or NaOH **in ethanol**, heat under reflux → **no reaction**

SUMMARY: NUCLEOPHILIC SUBSTITUTION MECHANISM

- Hydrolysis of bromoethane

$CH_3CH_2Br + NaOH(aq) \xrightarrow{heat} CH_3CH_2OH + NaBr(aq)$
bromoethane — ethanol

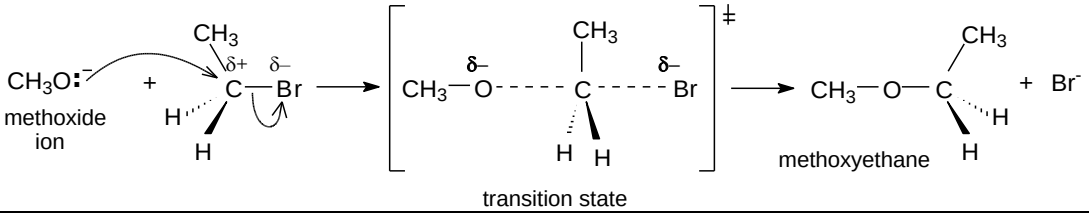
Mechanism: S_N2 (i.e. bimolecular nucleophilic substitution).



- Reaction between bromoethane and CH_3O^- (a negatively charged nucleophile)

$CH_3CH_2Br + CH_3O^- \xrightarrow{heat} CH_3CH_2–O–CH_3 + Br^-$
bromoethane — an ether

Mechanism: S_N2 (i.e. bimolecular nucleophilic substitution)

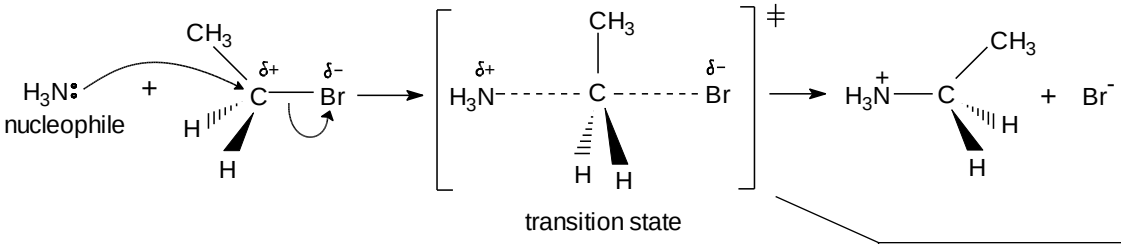


- Reaction of bromoethane with ammonia

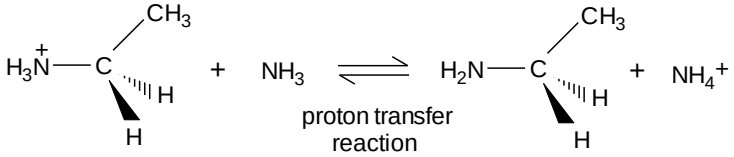
$CH_3CH_2Br + 2NH_3 \xrightarrow[\text{sealed tube, heat}]{\text{excess conc. } NH_3 \text{ (in alcohol)}} CH_3CH_2NH_2 + NH_4Br$

bromoethane — ethylamine

Mechanism: **S_N2 (i.e. bimolecular nucleophilic substitution)**.



Note: A proton transfer reaction next occurs to yield the $CH_3CH_2NH_2$.



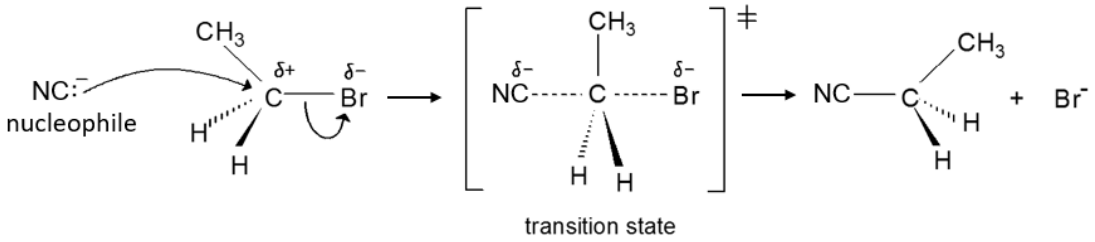
Note:
- Conservation of charge applies.
- This transition state has a net charge of zero because both reactants are uncharged.

- Reaction of bromoethane with ethanolic KCN

$CH_3CH_2Br + KCN \xrightarrow[\text{heat}]{\text{ethanolic KCN}} CH_3CH_2CN + KBr$

bromoethane — propanenitrile

Mechanism: **S_N2 (i.e. bimolecular nucleophilic substitution)**.

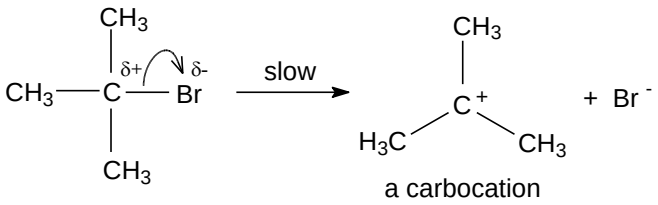


- Hydrolysis of 2-bromo-2-methylpropane

$(CH_3)_3CBr + NaOH(aq) \xrightarrow[heat]{} (CH_3)_3COH + NaBr(aq)$

Mechanism: **S_N1 (i.e. unimolecular nucleophilic substitution).**

Step 1: Formation of carbocation



a carbocation

Step 2: Nucleophilic attack by OH^-