

CARBOXYLIC ACIDS AND THEIR DERIVATIVES

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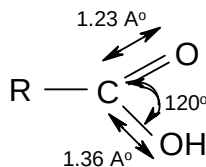
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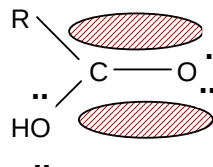
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The carboxyl functional group is represented as --COOH and is the end product of alcohol oxidation. The term carboxylic acid is little special in the sense that it represents two functional groups; first a carbonyl group and second hydroxyl group. One can say that in the carboxyl group a hydroxyl group is bonded to a carbonyl ($>\text{C}=\text{O}$) group. It is often represented as CO_2H or COOH . Carboxylic acids have been found to constitute one of the most frequently encountered classes of organic compounds. A large number of natural products are either carboxylic acids derivatives or are derived from them.

Molecular Structure of carboxylic acid



Orbital diagram of carboxylic acid



Nomenclature

The simplest carboxylic acid is formic acid (HCOOH). Its name has been derived from the Latin word *formica* which means ant. This acid was first obtained by distillation of ants and hence named as formic acid, which is its common name. Similarly acetic acid (CH_3COOH) was so named as it gives sour taste to vinegar. In Latin vinegar is called as *acetum* and hence the name acetic acid which is the chief constituent of vinegar. Many other carboxylic acids were also given names on the basis of their source. In the IUPAC system of nomenclature the carboxylic carbon is always numbered as 1 and hence must be located at the end of carbon chain. If other substituents are also present, they are named accordingly. The characteristic IUPAC suffix used for carboxylic acids is 'oic acid' which is replaced for last alphabet of name of alkane. For example CH_3COOH is a derivative of ethane and last 'e' of ethane is replaced by oic acid and it is called as ethanoic acid. The common names and IUPAC names for some carboxylic acids are given in Table 1.

Table 1 – Common names and IUPAC names of some carboxylic acids

No.	Carboxylic acid	common name	IUPAC name
1.	HCOOH	Formic acid	Methanoic acid
2.	CH_3COOH	Acetic acid	Ethanoic acid
3.	$\text{CH}_3(\text{CH}_2)_3\text{COOH}$	Valeric acid	Pentanoic acid
4.	$\text{CH}_3(\text{CH}_2)_{16}\text{COOH}$	Stearic acid	Octadecanoic acid
5.	$\text{CH}_3\text{CHOHCOOH}$	Lactic acid	2-Hydroxypropanoic acid
6.	$\text{C}_6\text{H}_5-\text{CHOHCOOH}$	Mandelic acid	2-Hydroxy-2-phenylethanoic acid
7.	$\text{CH}_2=\text{CHCOOH}$	Acrylic acid	2-Propenoic acid
8.	PhCOOH	Benzoic acid	Benzene carboxylic acid
9.	$\text{o-C}_6\text{H}_4(\text{OH})\text{COOH}$	Salicylic acid	o-Hydroxybenzene carboxylic acid
10.	HOOC-COOH	Oxalic acid	Ethanedioic acid
11.	$\text{HOOC-CH}_2\text{COOH}$	Malonic acid	Propanedioic acid
12.	$\text{HOOC-CH}_2\text{CH}_2\text{COOH}$	Succinic acid	Butanedioic acid
13.	$\text{o-HOOC-C}_6\text{H}_4\text{COOH}$	Phthalic acid	1,2-benzenedicarboxylic acid
14.	$\begin{array}{c} \text{H-C-COOH} \\ \\ \text{H-C-COOH} \end{array}$	Maleic acid	cis-2-butenedioic acid
15.	$\begin{array}{c} \text{H-C-COOH} \\ \\ \text{HOOC-C-H} \end{array}$	Fumaric acid	trans-2-butenedioic acid

An examination of Table 1 reveals that acids 1 to 4 are simple monocarboxylic acids i.e. they have only one COOH functional group. Compounds 5 and 6 possess hydroxyl as well as carboxylic groups. In such cases they are named as hydroxyl derivatives of carboxylic acids rather than carboxyl derivative of alcohols. The presence of a double bond in the main chain is represented by ending the name as 'enoic acid' and the position of double bond is designated by a numerical prefix as shown in compound 7. If the presence of a double bond causes geometrical isomerism in the compound, the stereochemistry is specified using *cis-trans* or E-Z notation. In case of aromatic carboxylic acids, whenever COOH is attached to benzene ring, the name of parent ring is retained and the suffix 'carboxylic acid' is added. In cases when some other groups are also present in the benzene ring the position of carboxylic acid group is described with respect to the other group as shown for compound 9. Compounds 11,12,14,15 possess two carboxylic acid groups and are named as dioic acids whereas, if the two carboxylic acid groups are in the benzene ring it is named as dicarboxylic acid as shown for compound 13. If hydroxyl function of carboxylic acids is replaced by other functional group, they are named as derivatives of carboxylic acids. Four common derivatives of carboxylic acids are-

a. Acyl halides
$$\text{R} - \underset{\text{X}}{\overset{\text{O}}{\text{C}}} = \text{O}$$
 where X = halogen

For example CH_3COCl is called as Acetyl chloride

b. Acid amides
$$\text{R} - \underset{\text{X}}{\overset{\text{O}}{\text{C}}} = \text{O}$$
 where X = NH_2

For example CH_3CONH_2 is named as Acetamide

c. Acid anhydride
$$(\text{R} - \overset{\text{O}}{\text{C}} = \text{O})_2\text{O}$$

For example if $\text{R} = \text{CH}_3$ it is acetic anhydride

d. Esters
$$\text{RCOOR}'$$

For example if $\text{R} = \text{R}' = \text{CH}_3$

The ester is named as methyl acetate

Physical Properties

Physical properties (for example boiling point and solubility) of carboxylic acids are governed by their ability to form hydrogen bonds.

(i) Melting and boiling point

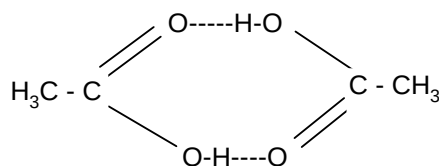
The melting and boiling points for a homologous series of carboxylic acids show some general features. For example, the boiling points of carboxylic acids increase with increase in size in a regular manner. However, the melting points do not show a regular trend. Unbranched carboxylic acids having an even number of carbon atoms exhibit melting points higher than odd numbered homologue having one carbon higher or lower. This behaviour probably reflects the difference in intramolecular force in the crystalline state. If the carboxylic acid possesses a *cis*

double bond, the melting points are significantly lowered. Table 2 presents boiling point and water solubility of some similar sized polar compounds (the non polar hydrocarbon hexane is provided for comparison).

Table 2- Boiling points and water solubility of some organic compounds

Formula	IUPAC name	Molecular weight	Boiling point (°C)	Water solubility
$\text{CH}_3(\text{CH}_2)_2\text{CO}_2\text{H}$	butanoic acid	88	164	very soluble
$\text{CH}_3(\text{CH}_2)_4\text{OH}$	1-pentanol	88	138	slightly soluble
$\text{CH}_3(\text{CH}_2)_3\text{CHO}$	pentanal	86	103	slightly soluble
$\text{CH}_3\text{CO}_2\text{C}_2\text{H}_5$	ethyl ethanoate	88	77	moderately soluble
$\text{CH}_3\text{CH}_2\text{CO}_2\text{CH}_3$	methyl propanoate	88	80	slightly soluble
$\text{CH}_3(\text{CH}_2)_2\text{CONH}_2$	butanamide	87	216	soluble
$\text{CH}_3\text{CON}(\text{CH}_3)_2$	N,N-dimethylethanamide	87	165	very soluble
$\text{CH}_3(\text{CH}_2)_4\text{NH}_2$	1-aminobutane	87	103	very soluble
$\text{CH}_3(\text{CH}_2)_3\text{CN}$	pentanenitrile	83	140	slightly soluble
$\text{CH}_3(\text{CH}_2)_4\text{CH}_3$	hexane	86	69	insoluble

Carboxylic acids and alcohols can form hydrogen bonds with each other and hence have higher boiling point than those of alkanes of similar size. The boiling point of carboxylic acids of similar size is still higher. This is because; here hydrogen bonding operates in a different way. In a pure carboxylic acid, hydrogen bonding can occur between two molecules of acid to produce a dimer as shown below.



This immediately doubles the size of the molecule and therefore increases the Vander waal dispersion forces between one of these dimers and its neighbours, resulting in a high boiling point.

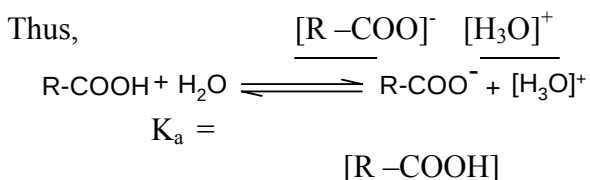
(ii) Solubility in water

The carboxylic acid do not dimerize in the presence of water. Instead, hydrogen bonds are formed between water molecules and individual acid molecules. Hence, carboxylic acid upto

four carbon atoms are fairly soluble in water. However, solubility decreases rapidly with increase in hydrophobic part (hydrocarbon tail) of carboxylic acid molecules. This is because the longer hydrocarbon chain of acid molecules tends to break hydrogen bonds. Thus, strong hydrogen bonds are replaced by weaker vander waal dispersion forces in such cases.

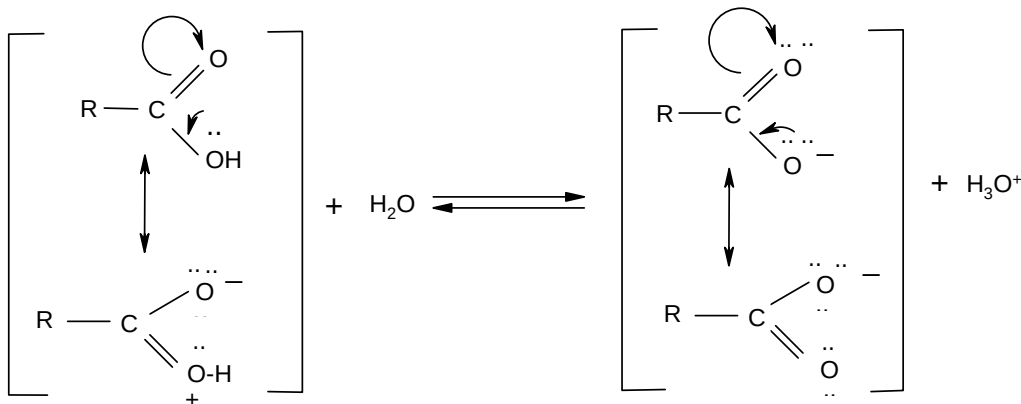
Acidity of Carboxylic Acids

The acidity of a carboxylic acid can be defined as the ease with which it can release a proton. The acid base equilibrium for a carboxylic acid can be represented by the equation -



and as $\text{pK}_a = -\log K_a$

The lesser the value of pK_a stronger is the acid. In an acid – base equilibrium water is the standard base used for pK_a measurements. Thus, anything that stabilizes the conjugate base (RCOO^-) will make it stronger. In such a case the equilibrium will shift to the right side. The carboxyl group and carboxylate anion are stabilized by resonance, however, the stabilization of anion will be much more than that of carboxylic acid. The reason is that the two contributing structures in carboxylate anion are equivalent as the C-O bonds are of equal length. The stabilization of resonance structures of anions leads to a markedly increased acidity to carboxylic acids.



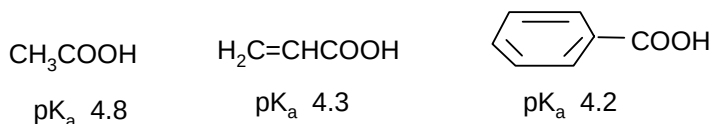
The pK_a 's of some typical carboxylic acids are presented in Table 3.

Table 3 – pK_a of some typical carboxylic acids

Acids	pK_a
HCOOH	3.75

CH ₃ COOH	4.74
FCH ₂ COOH	2.65
ClCH ₂ COOH	2.85
BrCH ₂ COOH	2.90
ICH ₂ COOH	3.10
Cl ₂ CHCOOH	1.30
Cl ₃ CCOOH	0.90
CH ₃ CH ₂ COOH	4.90
CH ₃ OCH ₂ COOH	3.60

The presence of electron donating or electron withdrawing groups also affects the acidity of carboxylic acids due to inductive effect exhibited by them. The electron-donating group near the carboxylic group makes removal of proton difficult whereas, an electron-withdrawing group facilitates the removal of proton and thereby makes the acid stronger. For example, acetic acid is a weaker acid than formic acid; it can be explained on the basis of electron donating nature of methyl group relative to hydrogen. On the other hand the presence of electron-withdrawing substituents increase the acidity. Also higher the electronegativity of the substituent, the greater is increase in acidity (compare the pK_a of F, Cl, Br and I substituted acids in Table 3). Monohalo acids are about 100 times more acidic than acetic acid whereas, trichloroacid is nearly 7000 times more acidic than acetic acid. Similar behaviour is also observed in benzoic acids. The substituents like methoxy, ethoxy, methyl, hydroxy etc decrease the acidity whereas, chloro,



nitro, bromo increase the acidity. Similar behaviour can be seen in substituted benzoic acids. Benzoic acid itself is a stronger acid than acetic acid due to presence of phenyl ring. The carboxyl group attached to sp²- hybridized carbon ionizes to a greater extent than attached to sp³- hybridized carbon. Electron-withdrawing capacity of carbon increases with increase in s character such as

The effect of substituents in benzoic acids is given in Table 4

Table 4- Effect of substituents on acidity of substituted benzoic acids.

Substituent X in XC ₆ H ₄ COOH	pK _a for different positions in the ring		
	<i>ortho</i>	<i>meta</i>	<i>para</i>
H	4.2	4.2	4.2
CH ₃	3.9	4.3	4.4
F	3.3	3.9	4.1
Cl	2.9	3.8	4.0

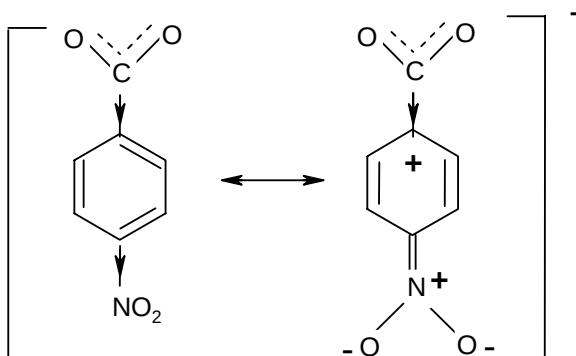
Br	2.8	3.8	4.0
I	2.9	3.9	4.0
OCH ₃	4.1	4.1	4.5
NO ₂	2.2	3.5	3.4

It is clear from Table 4 that the largest effect are observed when the strongly electron-withdrawing group is present at *ortho* position with respect to the carboxyl group. In contrast to *ortho* position, the effect observed at *meta* and *para* positions is relatively small.

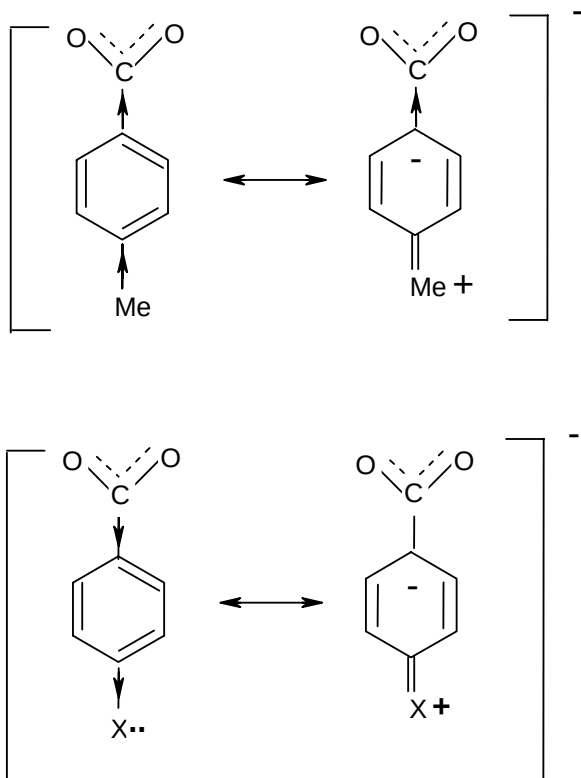
Alcohols also release protons, however, as compared to acids, the release of proton is slow. The reason is that the alkoxide ion obtained has only one structure due to which its stability is much less as compared to carboxylate ion. Thus, an alkoxide ion does not show resonance and is responsible for a very weak acidity of alcohols.

Resonating structures in presence of electron-releasing groups like methyl and substituted methyl groups are as follows.

Resonating structures in presence of electron-withdrawing substituents like NO₂ are as follows.



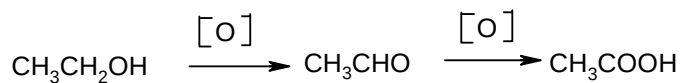
Resonating structures in the presence of substituents like Cl, Br, OCH₃, OH groups are as follows.



Preparation of Carboxylic Acids

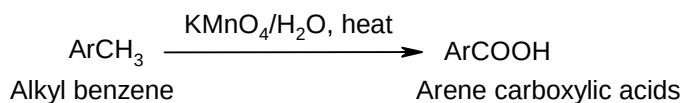
Many of the chemical reactions used for the preparation of carboxylic acids are oxidation reactions as the oxidation state of carbon in carboxylic acids is high. Some methods are

1. By oxidation of aldehydes or alcohols

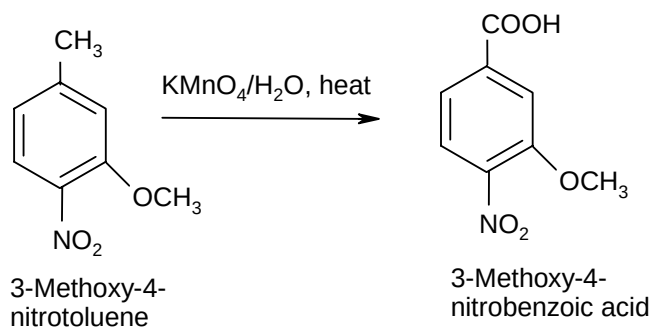


A large number of oxidizing agents such as KMnO_4 , H_2CrO_4 (Jones's reagent), $\text{K}_2\text{Cr}_2\text{O}_7$ can be used for these conversions.

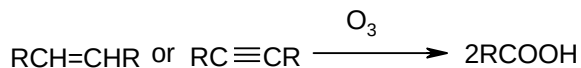
Oxidation of alkyl side chain in aromatic compounds also give corresponding carboxylic acid



2. Oxidative cleavage of alkenes and alkynes

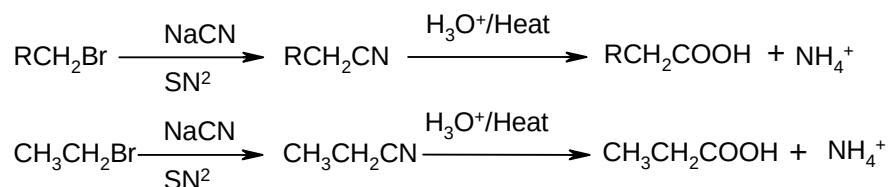


The cleavage of double or triple bonds by oxidizing agents give corresponding acids



3. By the hydrolysis of nitriles

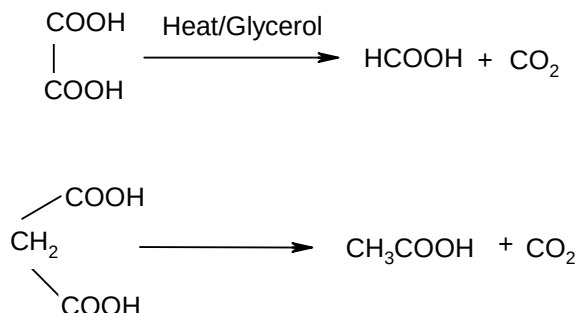
Generally, nitriles are prepared from organic halogen compounds and the hydrolysis then gives corresponding carboxylic acid



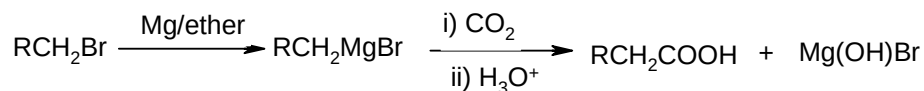
The hydrolysis may be carried out in acidic or alkaline medium; however, in the basic medium the salt of carboxylic acid is obtained.

4. By heating dicarboxylic acids

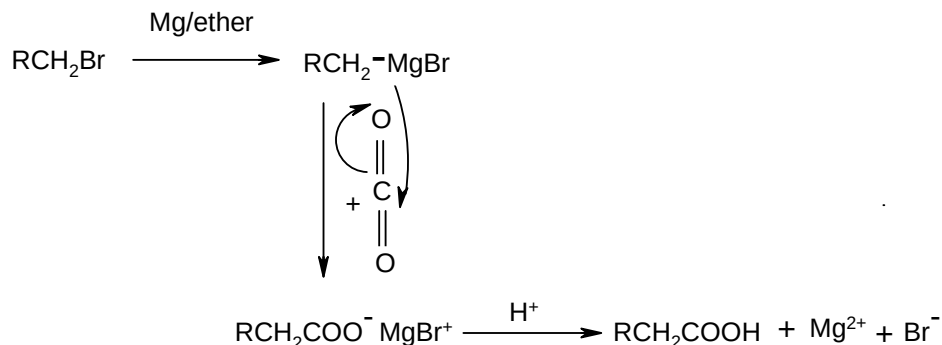
If dicarboxylic acids such as oxalic acid or malonic acids are heated, a molecule of carbon dioxide is eliminated and a monocarboxylic acid is obtained.



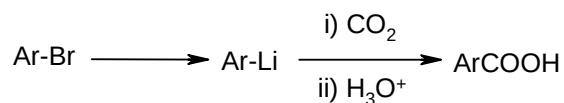
5. An alkyl halide can also be first converted to the corresponding Grignard reagent by treatment with Mg/ether. The Grignard reagent then adds to CO₂ to give carboxylic acid, which is obtained from the solution by treatment with strong aqueous acid.



Mechanism

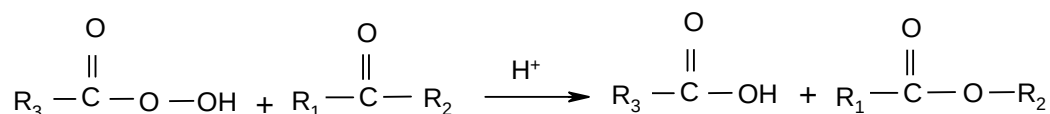


If aryl halides are taken in place of alkyl halides than a simple reaction with lithium gives aryllithium, which on treatment with CO_2 followed by hydrolysis gives aromatic acids.

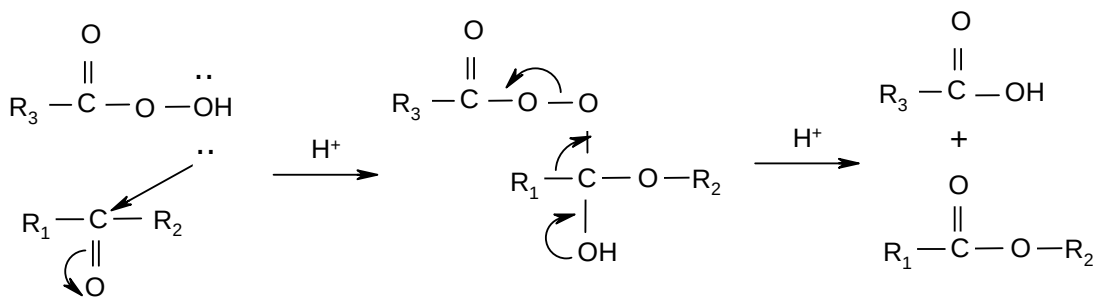


6. From peroxy acids – Baeyer – Villiger oxidation

Reaction of peroxyacid with carbonyl compound in the presence of an acid results in the formation of carboxylic acid along with ester.



Mechanism

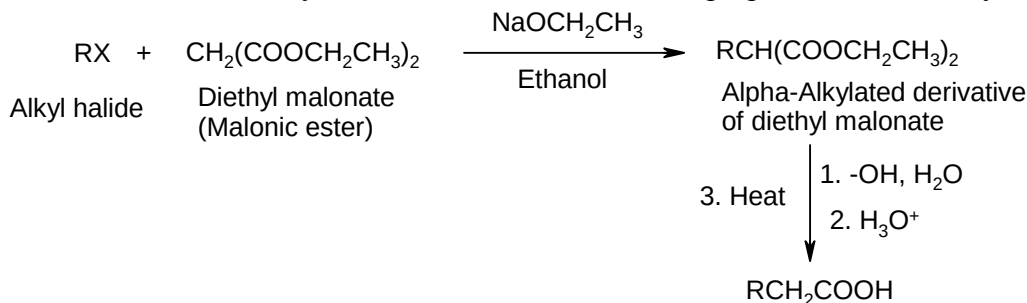


Step 1 involves addition of peroxyacid to the carbonyl compound

Step 2 is a concerted migration of one of the adjacent carbons to oxygen with loss of carboxylic acid.

7. The Malonic ester synthesis

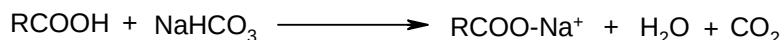
The malonic ester synthesis method is used for the preparation of carboxylic acids.



Chemical Properties

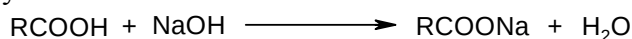
The reactions of carboxylic group can be divided into three types i.e i) Reactions due to hydroxyl hydrogen and ii) Reactions due to hydroxyl group and iii) reactions due to alkyl group. Let us discuss them one by one.

- i) Reactions due to hydroxyl hydrogen – Because of their acidic nature these compounds readily react with base in polar medium to form corresponding ionic salts which are soluble in water. For example

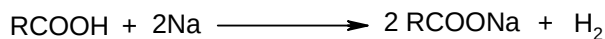


The evolution of CO_2 can be confirmed by passing the gas in limewater, which will turn white. This is a test for the presence of carboxylic acids in a mixture. The carboxylic acids having six or more than six carbon atoms exhibit slightly different behaviour in water as they possess hydrophobic alkyl group and hydrophilic carboxylic group in the same molecule. Due to this, these compounds form micelles in water.

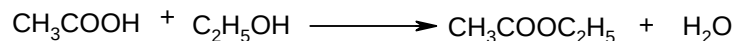
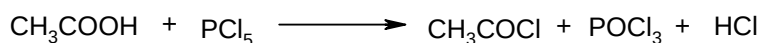
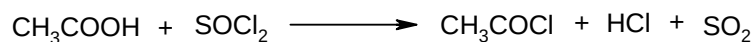
Carboxylic acids neutralize alkali and salts are obtained



However, if strong electropositive metals are taken evolution of hydrogen takes place

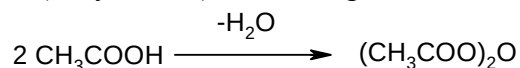


- ii) Reactions due to hydroxyl group– In these reactions hydroxyl group is replaced by another nucleophilic group. These types of reactions are useful for preparing various derivatives of carboxylic acids. It is well known that OH is a poor leaving group and hence it is helpful to convert it to a better leaving group such as Cl or Br etc. Some common reactions are as follows.

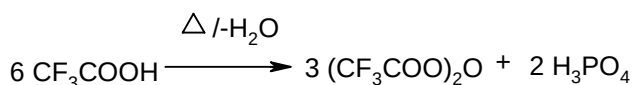


The last reaction is called esterification as it converts acid to its ester derivative.

If vapours of acetic acid are passed over a heated catalyst at higher temperature (900 K), loss of water (dehydration) occurs to give acetic anhydride.



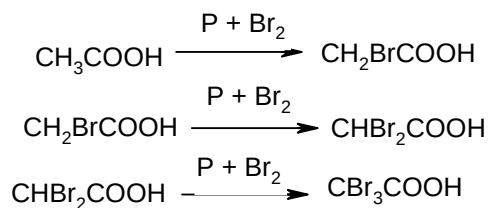
Trifluoroacetic acid, which is one of the stronger acids on simple heating, gives the corresponding anhydride



iii) Alpha-halogenation of aliphatic acids: Reactions due to alkyl group

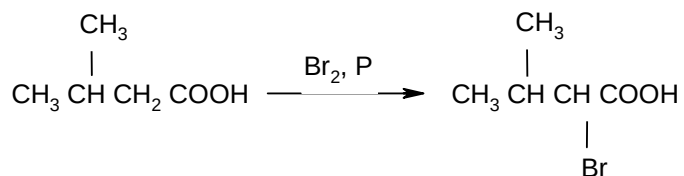
Hell-Volhard-Zelinsky Reaction

Reaction of carboxylic acids with phosphorus and bromine or chlorine or phosphorus halides replaces the hydrogen of α carbon atom. The best condition for the reaction is diffused sunlight or halogen carrier in presence of phosphorous. All the hydrogens of alkyl group can be replaced successively.



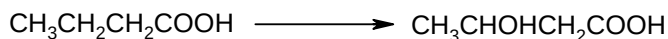
This method of α -bromination of carboxylic acids is called as Hell-Volhard-Zelinsky Reaction . If the acid is RCH_2COOH , the replacement of hydrogens will occur only at α carbon i.e. at adjacent to carboxylic group.

If carboxylic acids are treated with mild oxidizing agents such as hydrogen peroxide, oxidation



occurs at β -carbon atom. For example

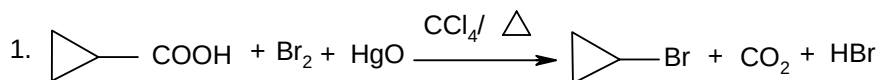
$\gamma \quad \beta \quad \alpha$



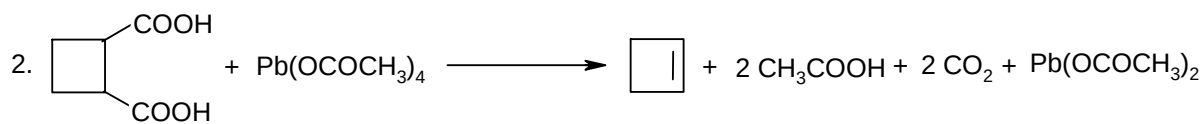
iv) Oxidation and reduction reactions

Oxidation

As the oxidation state of carbon in carboxylic acids is maximum, further oxidation causes removal of carbon as carbon dioxide. Following are some typical examples-

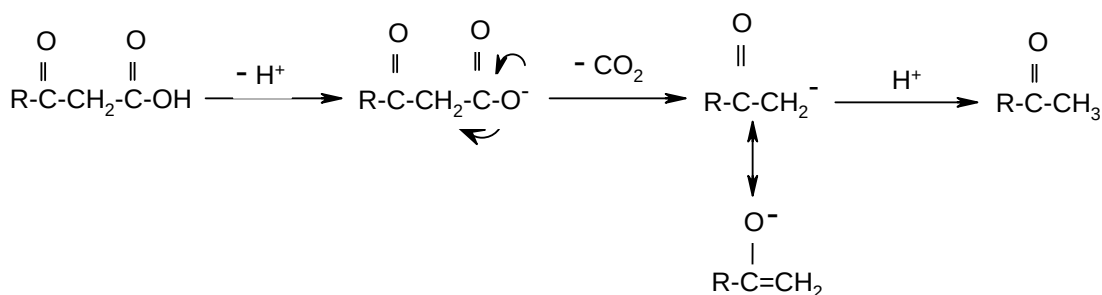


Cyclopropane
carboxylic acid

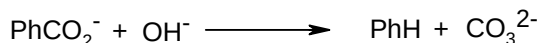


Cyclobutane 1,2-
dicarboxylic acid

The reaction where a carboxylic acid loses CO_2 is called decarboxylation. The unusual stability of carbon dioxide indicates that decarboxylation reaction is exothermic, however, in practice it is not always easy to carry out decarboxylation. Acids, which possess a carbonyl group at β -position decarboxylates readily on heating at 373–423 K.

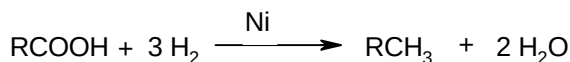


The reason for this ease of decarboxylation is that when carboxyl group decarboxylates, it forms a resonance-stabilized anion as shown above. This anion is much more stable than anion RCH_2^- which will be produced by a simple carboxylic acid. Aromatic carboxylic acids decarboxylate when their salts are heated with copper and quinoline.

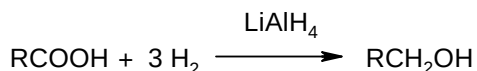


Reduction

In general, carboxylic acids are resistant to reduction, however, at high temperature and pressure with HI and red phosphorus or with hydrogen in presence of nickel catalyst corresponding alkane are obtained.



If carboxylic acids are treated with a powerful metal hydride reagent such as lithium aluminium hydride corresponding primary alcohol is obtained.

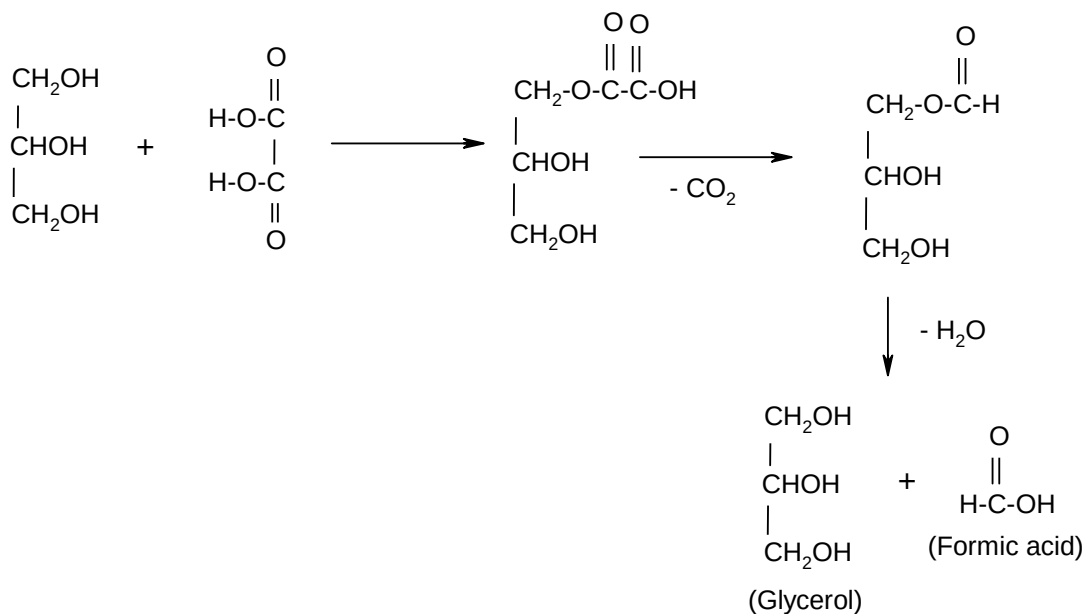


Nearly one third of the metal hydride is lost as hydrogen gas and the initial product formed is a metal salt (RCH_2OM), which must be hydrolyzed to give the corresponding alcohol.

Two Individual members Formic Acid and Acetic Acid

Formic Acid

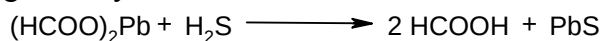
Formic acid (methanoic acid) is the first member of carboxylic acid series and is widely used in preservation and is also used as an antiseptic. It is also used in dyeing of wool and cotton fabrics. It is normally prepared in the laboratory by heating glycerol ($\text{CH}_2\text{OH}.\text{CHOH}.\text{CH}_2\text{OH}$) with oxalic acid at 380 K. The details of this reaction are already taught at +2 level and hence are not discussed here.



Reactions

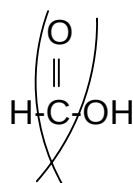
The final products of the reaction are glycerol and formic acid and hence after distilling formic acid, regenerated glycerol further reacts with fresh oxalic acid to give formic acid. Thus small amount of glycerol is enough to convert large amount of oxalic acid. The formic acid so obtained is not anhydrous and cannot be made anhydrous by simple distillation because the boiling point of formic acid is 373.5 K, which is very close to the boiling point of water. Therefore, the aqueous solution is neutralized with lead carbonate and concentrated to get

crystals of lead formate. The crystals are dried and heated at 373 K in presence of H_2S gas to give anhydrous formic acid.



Properties

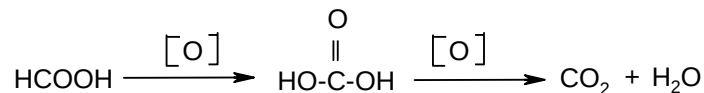
It is a colorless, pungent liquid, which is miscible in water, alcohol and ether in any proportions. If we look at the structure of formic acid, it is clear that it has both an aldehyde as well as carboxylic groups as shown below



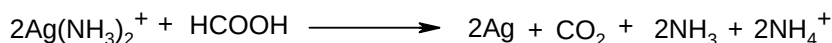
due to which it exhibits properties of aldehyde as well as of acids. Formic acid is a strong acid and is nearly 12 times stronger than acetic acid.

Reactions due to aldehyde group

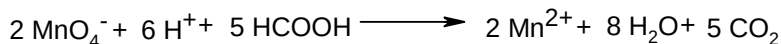
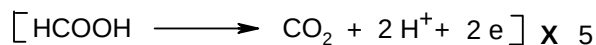
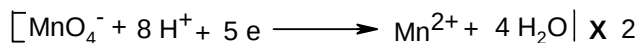
1. Like aldehydes, formic acid reduces mercuric chloride, ammonical silver nitrate, acidified KMnO_4 and itself gets oxidized to carbonic acid.



The reaction for reduction of ammonical silver nitrate to silver mirror by formic acid is –



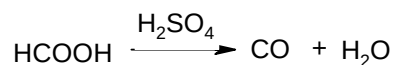
Similarly decolourisation of acidified KMnO_4 by formic acid can be represented as-



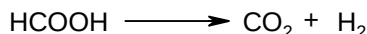
2. Some other reactions-

i) On treatment with concentrated sulphuric acid, formic acid readily undergoes dehydration to give carbon monoxide and water. The method is widely used for the preparation of carbon monoxide.

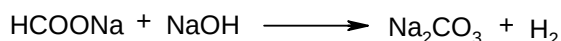
ii) On heating at 430 K under pressure formic acid undergoes decomposition to give carbon



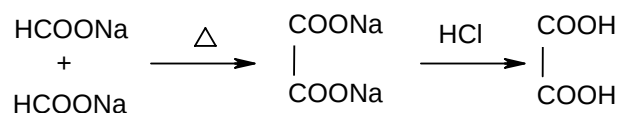
dioxide and hydrogen.



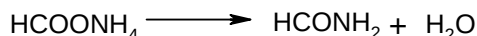
iii) Sodium or potassium formate on heating with soda lime gives hydrogen.



However, if the formates are heated strongly (630 K) they lose hydrogen and oxalate is obtained. The oxalate on treatment with dilute HCl gives oxalic acid.



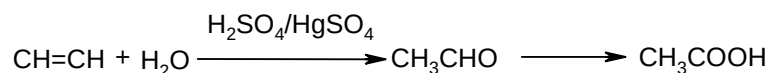
The ammonium salt of formic acid on heating gives formamide



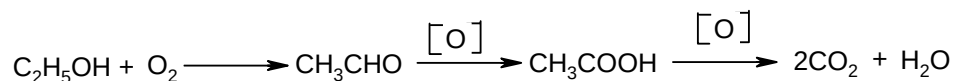
The test of formic acid or formates is that they give red colour with neutral FeCl_3 [i.e ferric chloride neutralized with ammonia solution]. They form silver mirror with ammonical silver nitrate solution and also on heating with sulphuric acid evolve carbon monoxide, which burns with blue flame.

Acetic Acid

The IUPAC name of acetic acid is ethanoic acid, which is found in number of fruit juices and is one of the most common organic acids. It is the main constituent of vinegar and can be prepared by any of the general methods reported earlier. However, industrially it is prepared by passing acetylene gas through a solution of 42 % sulphuric acid having 1 % mercuric sulphate. The temperature is maintained at 333 K and the product obtained is acetaldehyde. Further on passing the vapours of acetaldehyde and air over a catalyst (manganese acetate) gives acetic acid.



Acetic acid can also be prepared by quick-vinegar process in which oxidation of fermented liquors (10-15 % alcohol) is carried out by air in presence of microorganism *mycoderma aceti*. In this process the supply of air should be carefully controlled. If air is too less the product will be aldehyde and if air is too much, the product will be carbon dioxide.



Details have already given in +2 textbooks.

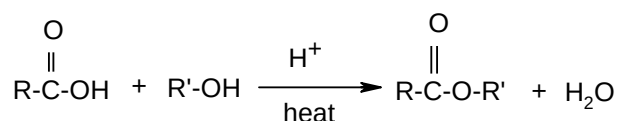
Physical properties

Acetic acid is colourless liquid having pungent smell. It is used as a solvent for large number of organic compounds. It exhibits properties as have been already described as general properties of carboxylic acids. The dilute acid (10-12 %) is called vinegar. It is used in the preparation of dyes, drugs, paints and perfumes.

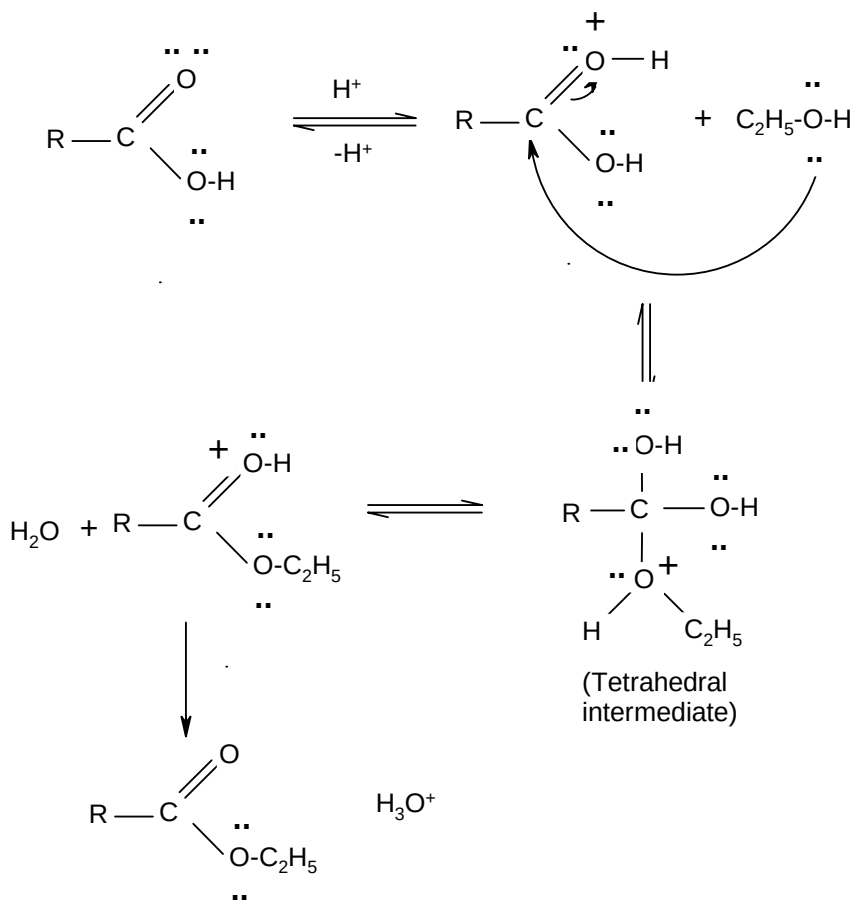
Chemical properties

(i) Esterification

Esterification is a process used for the preparation of esters by the reaction of carboxylic acids with alcohols in the presence of an acid.



Esters can also be made from other carboxylic acid derivatives specially acyl halides and acid anhydrides, by treating them with an appropriate alcohol in the presence of weak base. The mechanism of esterification can be represented as follows-



This mechanism is generally referred to as A_{AC}2 (Acid catalyzed, acyl oxygen cleavage, bimolecular reaction).

Step 1 An acid/base reaction, protonation of the carbonyl makes it more electrophilic.

Step 2 The –O– atom of alcohol functions as nucleophile attacking the electrophilic –C– in the C=O, with the electrons moving towards the oxonium ion creating the tetrahedral intermediate.

Step 3 An acid/base reaction, which deprotonate the alcoholic oxygen atom.

Step 4 An acid/base reaction, to remove the –OH group. It is important to first convert it into better leaving group by protonation. Electron pair of an adjacent oxygen atom helps in removing the leaving group.

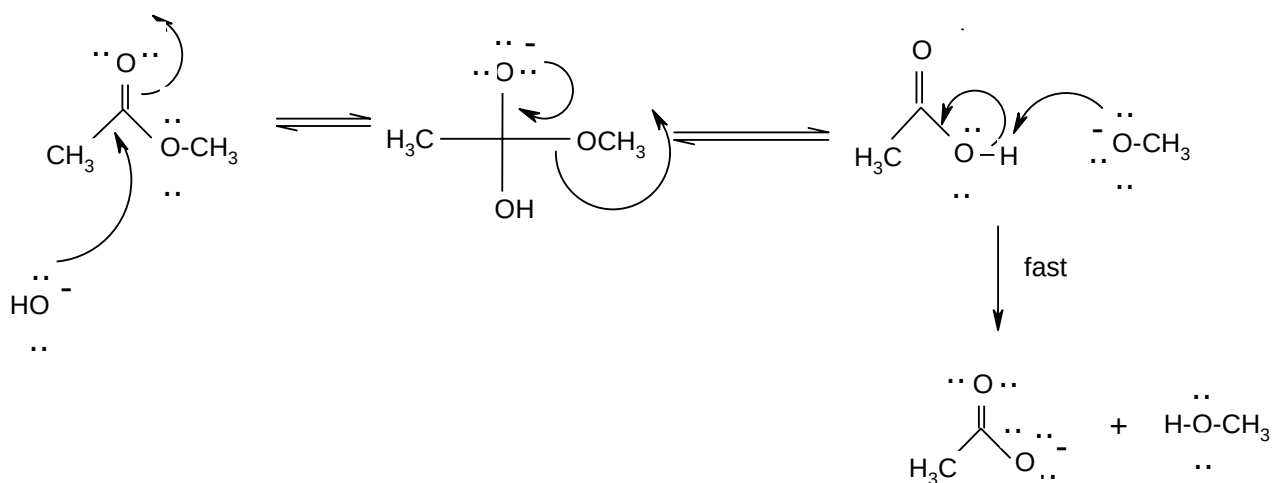
Step 5 An acid/base reaction, deprotonation of the oxonium ion reveals the carbonyl in the ester product.

(ii) Hydrolysis of esters

Esters undergo hydrolysis to the parent carboxylic acid and an alcohol both in the presence of aqueous acid or base with different mechanisms as shown below

a) Reaction under basic conditions

Alkaline/basic hydrolysis of esters is called as “saponification” because it is the basis of making soap.



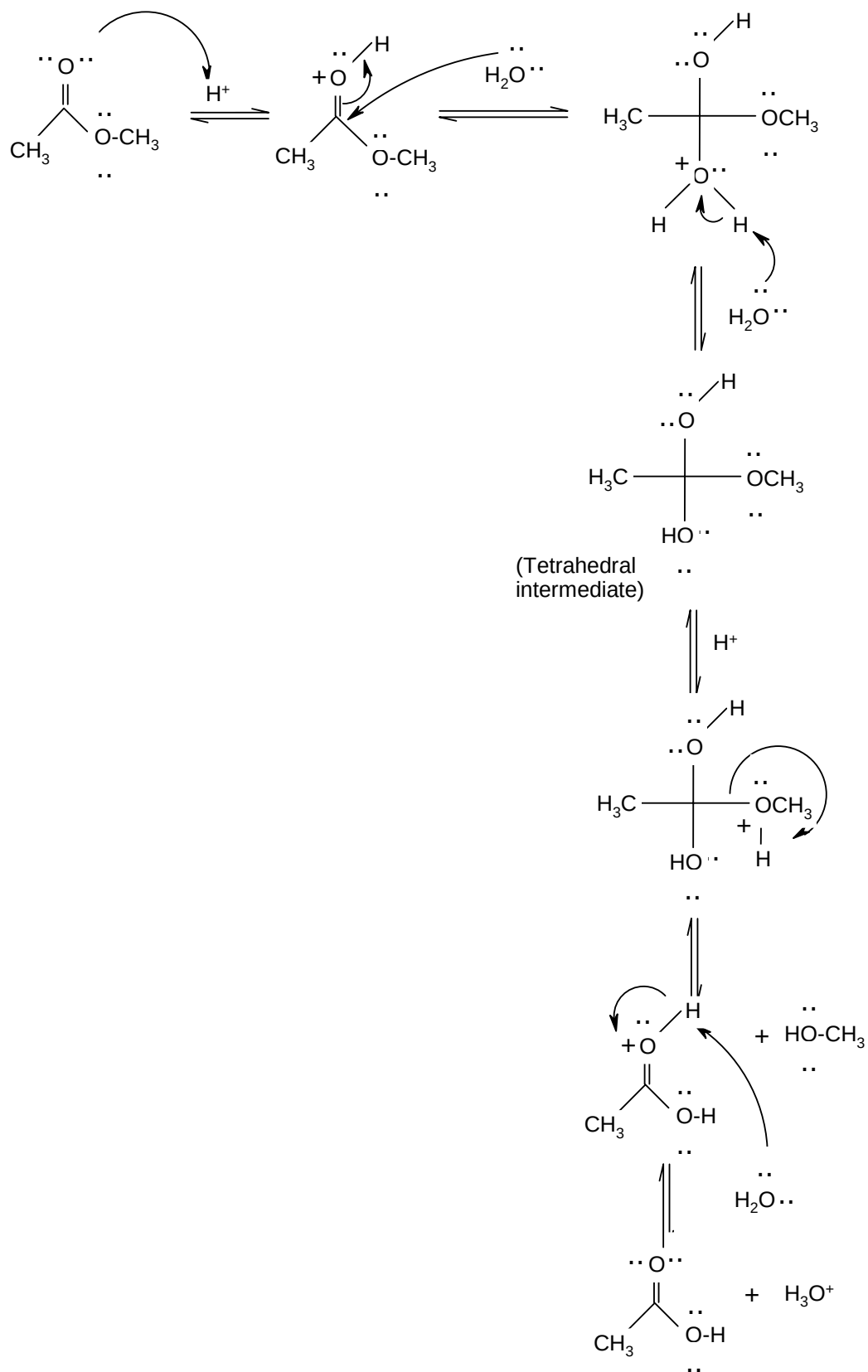
Step 1 the nucleophile (OH^-) attacks at the electrophilic $-\text{C}-$ of the ester $-\text{C}=\text{O}$, breaking the π bond and creating the tetrahedral intermediate.

Step 2 the intermediate collapses, reforming the $-\text{C}=\text{O}$ results in the loss of the leaving group the alkoxide (RO^-), leading to the carboxylic acid.

Step 3 is an acid/base reaction. The equilibrium exists where an alkoxide (RO^-) functions as a base deprotonating the carboxylic acid (RCO_2H).

b) Reaction under acidic conditions:

The mechanism of acid catalyzed hydrolysis is the reverse of Fischer esterification.



Step 1 is an acid/base reaction. To activate the ester protonation of the ester carbonyl group occurs to make it more electrophilic.

Step 2 the -O- atom of water functions as the nucleophile attacking the electrophilic -C- in the -C=O with the electron pair moving towards the oxonium ion creating the tetrahedral intermediate.

Step 3 an acid/base reaction, deprotonate the oxygen that came from the water molecule to neutralise the charge,

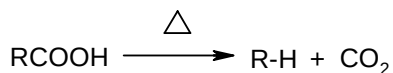
Step 4 an acid/base reaction, protonation of -OCH_3 group to convert it into better leaving group.

Step 5 electron pair of adjacent oxygen atom helps in removing the leaving group (a neutral methanol molecule).

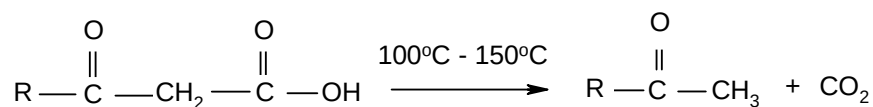
Step 6 is again an acid/base reaction, deprotonation of the oxonium ion reveals the carbonyl -C=O in the carboxylic acid product and regenerates the acid catalyst.

Mechanism of Decarboxylation

Loss of carbon dioxide is called decarboxylation. Simple carboxylic acids rarely undergo decarboxylation.



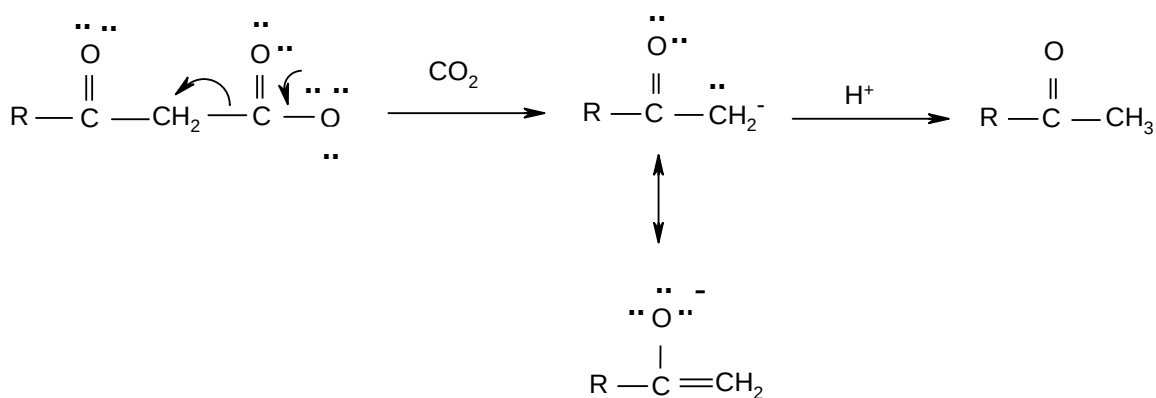
For example



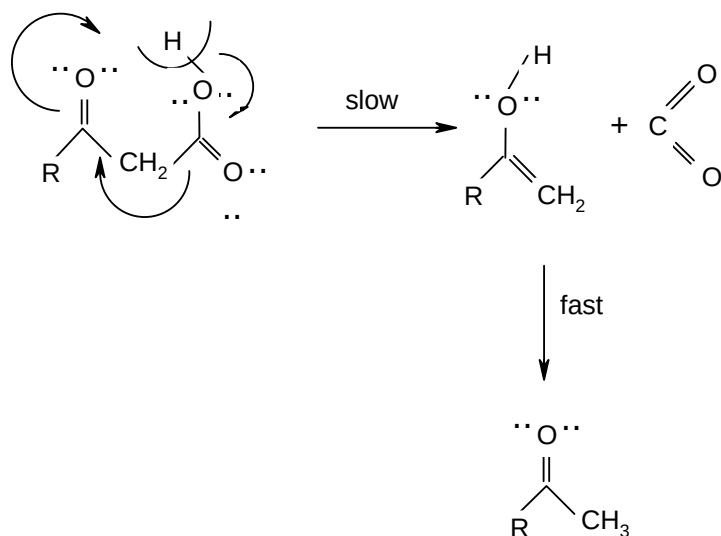
β -keto acid

Carboxylic acids with a carbonyl group at the 3- (or β -) position readily undergo thermal decarboxylation. There are two reasons for this ease of decarboxylation –

i) Carboxylate ion decarboxylates to form a resonance stabilized anion.



ii) When the acid itself decarboxylates, the reaction proceeds via six membered cyclic transition state giving an enol intermediate that tautomerises to the carbonyl compound.



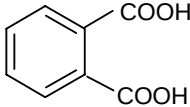
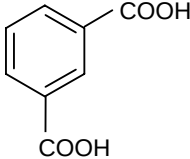
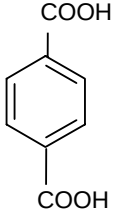
Step 1 is the concerted step in which cyclic transition step is involved. Protonation of the carbonyl group takes place with simultaneous breaking of the $-\text{OH}$ bond and formation of the π bond.

Step 2 Tautomerisation of the enol of the carboxylic acid leads to the acid product.

Dicarboxylic Acids

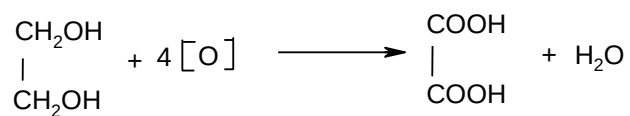
The general formula of saturated dicarboxylic acids is $\text{C}_n\text{H}_{2n}(\text{CO}_2\text{H})_2$ ($n = 0$ for oxalic acid).

Dicarboxylic acids are commonly known by names, which indicate their source. For example, oxalic acid ($\text{HO}_2\text{CCO}_2\text{H}$) occurs in plants of oxalis group. According to the I.U.P.A.C system of nomenclature, the class suffix is $-\text{dioic}$, e.g., succinic acid, $\text{HOOCCH}_2\text{CH}_2\text{COOH}$, is named as butanedioic acid; $\text{HOOCCH}(\text{CH}_3)\text{CH}(\text{CH}_3)\text{CH}_2\text{COOH}$ is named as 2,3-dimethyl pentanedioic acid. The common names of some aliphatic and aromatic acids are given below:

Structure	Common Name
	phthalic acid
	isophthalic acid
	terephthalic acid
HOOC - COOH	oxalic acid
HOOC CH ₂ COOH	malonic acid
HOOC (CH ₂) ₂ COOH	succinic acid
HOOC (CH ₂) ₃ COOH	glutaric acid
HOOC (CH ₂) ₄ COOH	adipic acid
HOOC (CH ₂) ₅ COOH	pimelic acid

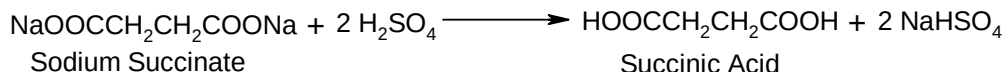
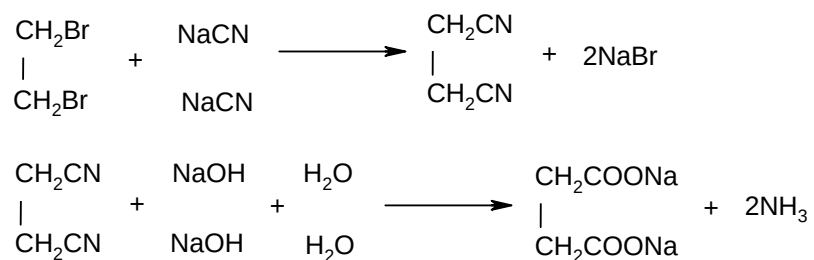
Methods of preparation of unsaturated monocarboxylic acids

1. From dihydric primary alcohols, by oxidation



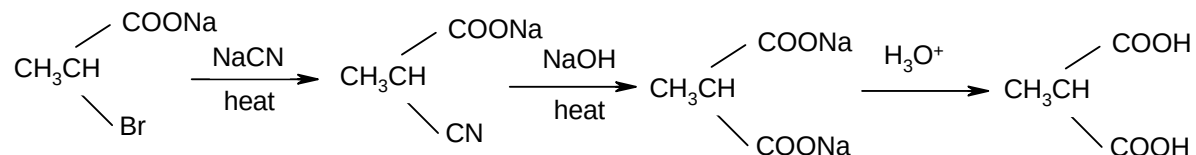
This is a general method of preparation of dicarboxylic acids.

2. From α,ω -dibromoalkanes (bromine attached to terminal carbon atoms), by means of the nitrile synthesis.



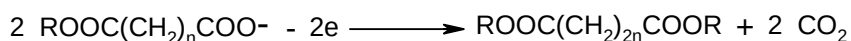
3. From α -bromoacids

The final products obtained are substituted malonic acid. Chloroacetic acid can be converted into malonic acid.



4. From potassium salts of half esters of dibasic acids by electrolysis

The intermediate in this reaction is $\text{ROOC}(\text{CH}_2)_n\text{COO}^-$. The ester formed by the electrolysis reaction may be saponified with a base and the dibasic acid may be obtained by acidification.



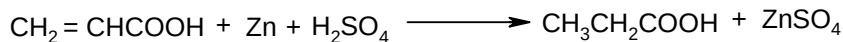
Effect of heating on Dicarboxylic Acids

At higher temperature these acids decompose in different ways. Oxalic and malonic acids decarboxylates with the formation of formic and acetic acid respectively; succinic and gluteric acids undergo dehydration with the formation of succinic and gluteric anhydrides, respectively; while heating of adipic and pimelic acids results in the formation of cyclopentanone and cyclohexanone, respectively, by the elimination of carbonic acid.

These compounds exhibit both the usual reactions of carboxylic acids as well as typical reactions of olefins. The double bond increases the acidity of carboxylic acids when it is present at α - position and to some extent it also increases the ease of decarboxylation. Following are the reactions shown by unsaturated monocarboxylic acids.

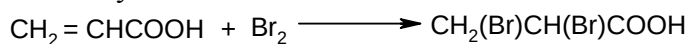
1. Reduction of double bond

The reduction of double bond occurs with sodium amalgum and water, with zinc and sulfuric acid, or with many other metals.



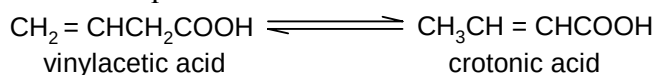
2. Addition of bromine

Bromine adds readily to unsaturated monocarboxylic acids but slowly to unsaturated dicarboxylic acids



3. Shifting of the double bond

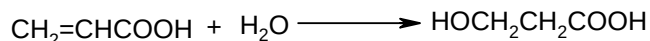
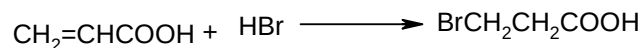
There is partial transformation of vinylacetic acid to crotonic acid or vice-versa when it is heated in aqueous basic solution. Both these acids are in equilibrium with each other.



4. Unsymmetrical addition

β -bromopropionic acid and β -hydroxypropionic acid are formed, respectively, when acrylic acid undergoes hydrogen bromide addition and hydration under basic conditions or slowly at 373 K in dilute aqueous acid

8. Polymerization

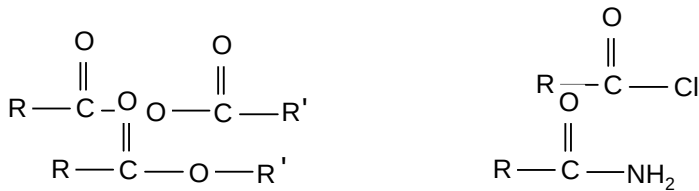


Exposure of higher unsaturated acids to air increases their viscosity and colour. This is due to the oxygen-induced polymerization. Esters of unsaturated acids like methyl acrylate and methyl methacrylate are converted into synthetic resins.

Derivatives of Carboxylic Acids

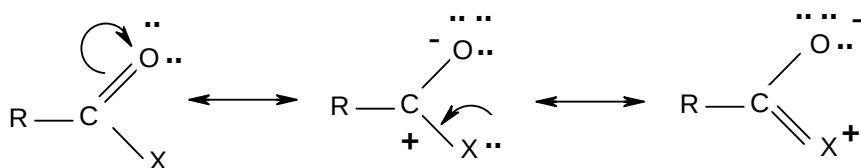
The combination of other functional groups with carbonyl group leads to the formation of carboxylic acid derivatives. The four important derivatives of carboxylic acids are acyl chlorides, acid anhydrides, esters and acid amides. They are called so because on hydrolysis carboxylic acids are produced.

The decreasing order of reactivity of these derivatives towards nucleophilic substitution reactions is:



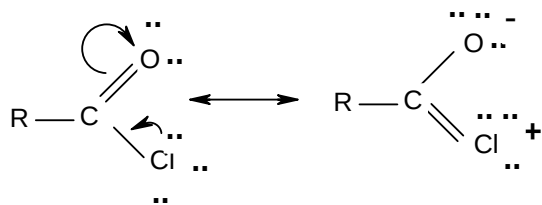
acyl chloride > anhydride > ester > amide

Which can be accounted for on the basis of electron donating properties of the substituent attached. The greater the electron donating properties of the substituent, slower is the rate. Electron release from the substituent X stabilizes the carbonyl group as well as decreases the



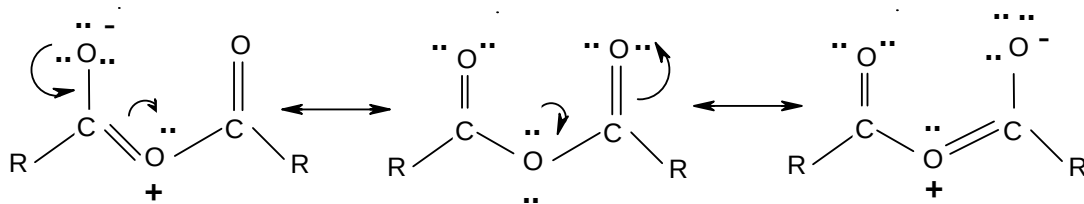
positive character of the carbonyl carbon and in turn making the carbonyl group less electrophilic.

In acyl chlorides, chlorine atom has lone pair of electrons but in resonance it exhibits as a poor electron donor.

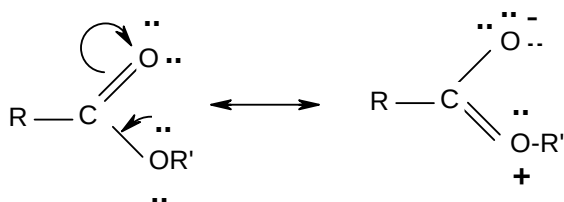


The lone pair orbital (3p) of chlorine do not overlap effectively with the π orbital of carbonyl group. Hence, destabilizes the carbonyl group in resonance and making it more reactive.

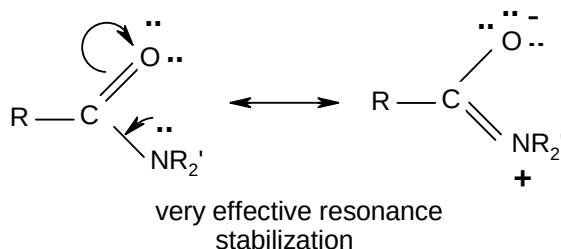
In acid anhydrides, carbonyl group is better stabilized by electron donation than acyl chlorides. Here electron pair orbital (2p) of oxygen overlap with the orbital of carbonyl group but the presence of two carbonyl groups create competition for the same electron pair. Hence, the extent of stabilization in resonance is decreased.



In case of esters carbonyl group is stabilized more effectively by the electron pair of oxygen than acid anhydride. Because, here only one carbonyl group is present, which increases the stability of carbonyl group of ester and decreases the reactivity towards nucleophilic attack.



However, in amides, nitrogen is less electronegative than oxygen and hence, stabilizes the carbonyl group of amides and further decreases the reactivity.

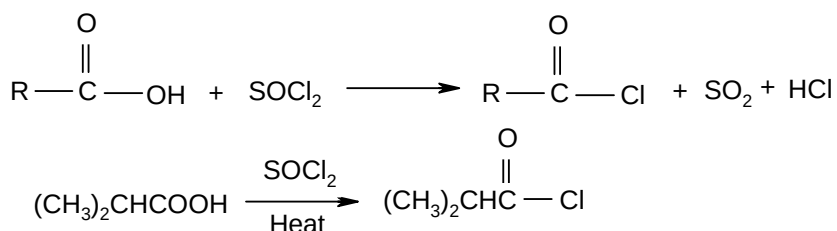


Acyl Chloride

1. Preparation

Acyl chlorides can be readily prepared from carboxylic acids by their reaction with thionyl chloride, PCl₅, PCl₃ and so on.

2. Physical properties



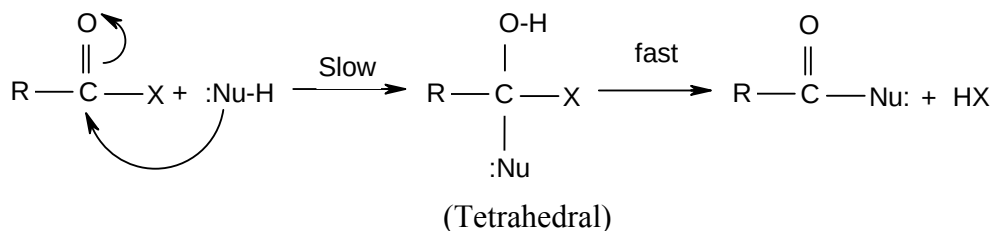
Acyl chloride like ethanoyl chloride is a colourless fuming liquid. The strong smell of ethanoyl chloride is a mixture of the smell of vinegar (ethanoic acid) and the acrid smell of hydrogen chloride gas. The reaction of ethanoyl chloride with water vapour in the air is the cause of the smell.

Acyl chlorides cannot dissolve in water because they react violently with it. Boiling point of ethanoyl chloride is 51°C, it is polar molecule having dipole-dipole attractions between its molecules as well as vander waal dispersion forces. However, it does not form hydrogen bonds. Its boiling point is therefore higher than an alkane of comparable size but less than the boiling point of alcohols of similar size.

3. Chemical properties

The treatment of an acyl chloride with an appropriate nucleophile may lead to an acid anhydride, an ester, an amide and carboxylic acid.

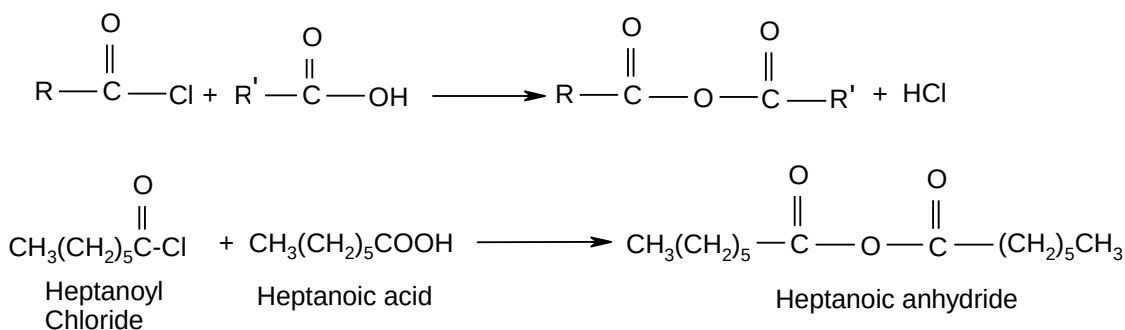
The nucleophilic acyl substitution follows a two-step mechanism and involves the formation of a tetrahedral intermediate.



Some common reactions involving conversion of acyl chlorides to various derivatives of carboxylic acid are as follows:

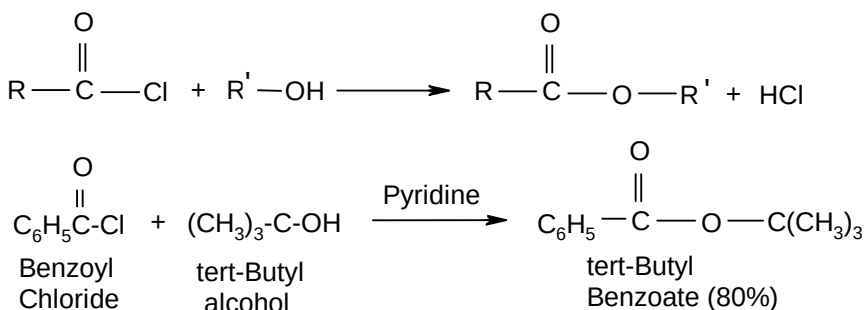
i) Reactions with carboxylic acids

The reaction of acyl chlorides with carboxylic acids yields an acid anhydride. This reaction is generally used for preparative purposes and a weak organic base such as pyridine is normally added as a catalyst. The base also neutralizes the hydrogen chloride formed.



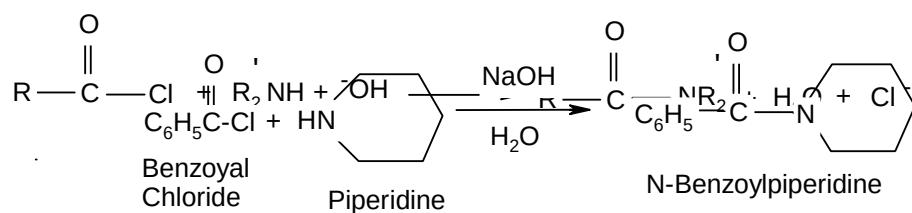
ii) Reaction with alcohols

The reaction of acyl chlorides with alcohols gives esters. The reaction is typically carried out in the presence of small amount of pyridine.



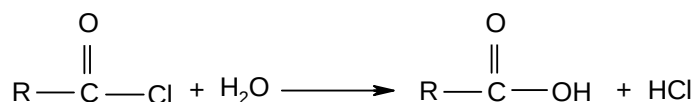
iii) Reaction with ammonia and amines

The reaction of acyl chlorides with ammonia and amines leads to the formation of amides. A base such as NaOH is normally added to neutralize the hydrogen chloride produced.

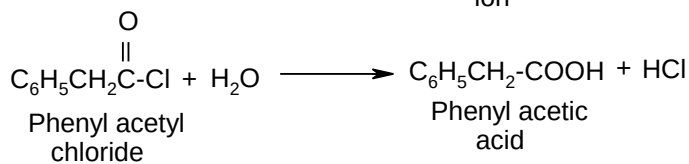
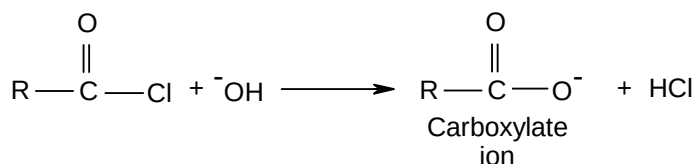


iv) Hydrolysis

The hydrolysis of acyl chlorides yields carboxylic acids. In basic medium, the product acid is converted to its carboxylate salt. It must be realized that the reaction has little synthetic value because the acyl chlorides are generally prepared from the carboxylic acid rather than vice-versa.



In basic medium



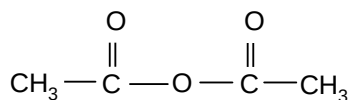
ESTERS

Acid Anhydrides

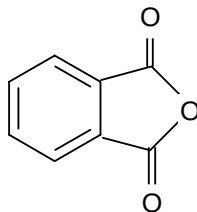
1. Preparation

Acetic anhydride, phthalic anhydride and maleic anhydride are industrially important chemicals. Out of these, phthalic anhydride and maleic anhydride possess anhydride function through a ring and are called as cyclic anhydrides.

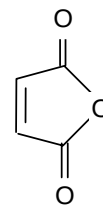
Acetic anhydride



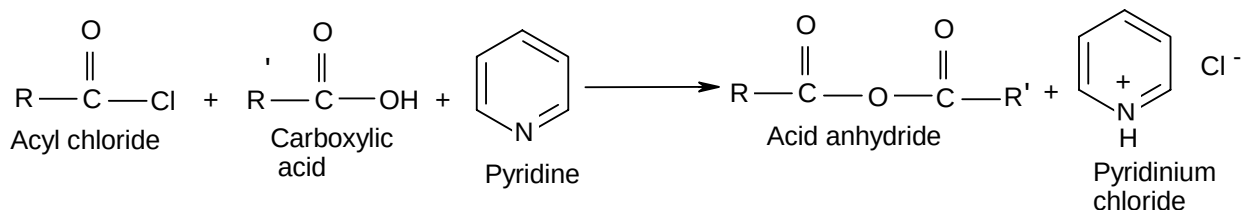
Phthalic anhydride



Maleic anhydride



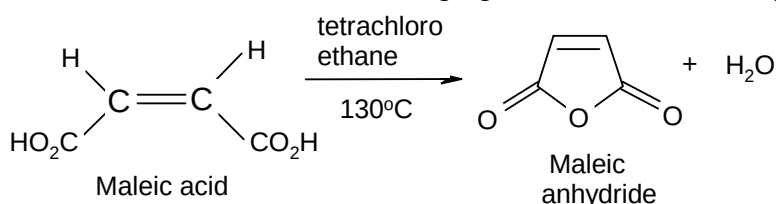
A simple laboratory method used for the synthesis of acid anhydrides is the reaction of acyl chlorides with a carboxylic acid.



This procedure is common and applicable for the preparation of symmetrical anhydrides (R and R' same) as well as mixed anhydrides (R and R' different).

For preparing cyclic anhydrides, in which the ring consists of five or six atoms are prepared by heating the corresponding dicarboxylic acids in an inert solvent medium.

The above method is used for the preparation of maleic anhydride from maleic acid (*cis*-form).



Fumaric acid (*trans*-form) cannot produce maleic anhydride because in maleic acid, orientation of two carboxylic acid groups is on one side which facilitates dehydration reaction and resulting in formation of cyclic maleic anhydride. However, on the contrary, in fumaric acid orientation of both the carboxylic acids a group lies opposite to each other. Hence, not facilitating the dehydration reaction.

2. Physical properties

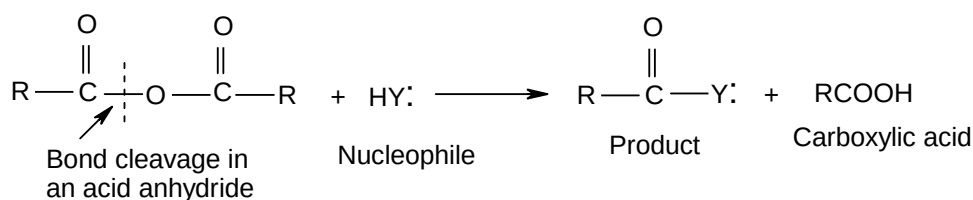
Ethanoic anhydride is a colourless liquid with a strong smell of vinegar. The cause of the smell is the reaction of ethanoic anhydride with water vapour in air resulting in the formation of ethanoic acid again.

Ethanoic acid is insoluble in water. Its boiling point is 140°C . This is because it is fairly big polar molecule with both vander waal dispersion forces and dipole-dipole attractions. It cannot

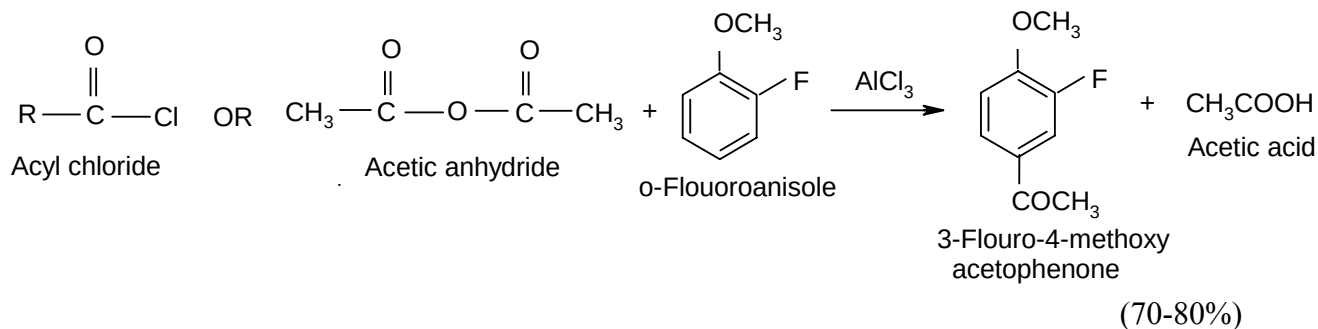
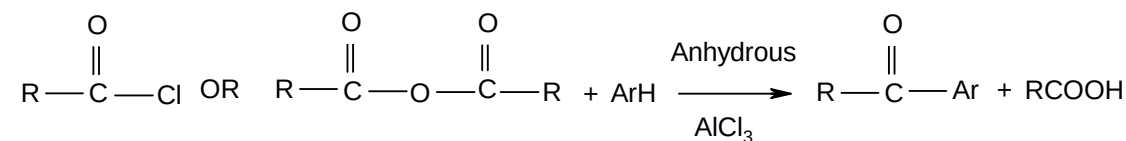
form hydrogen bonds and hence its boiling point is not as high as carboxylic acid of comparable size.

3. Chemical properties

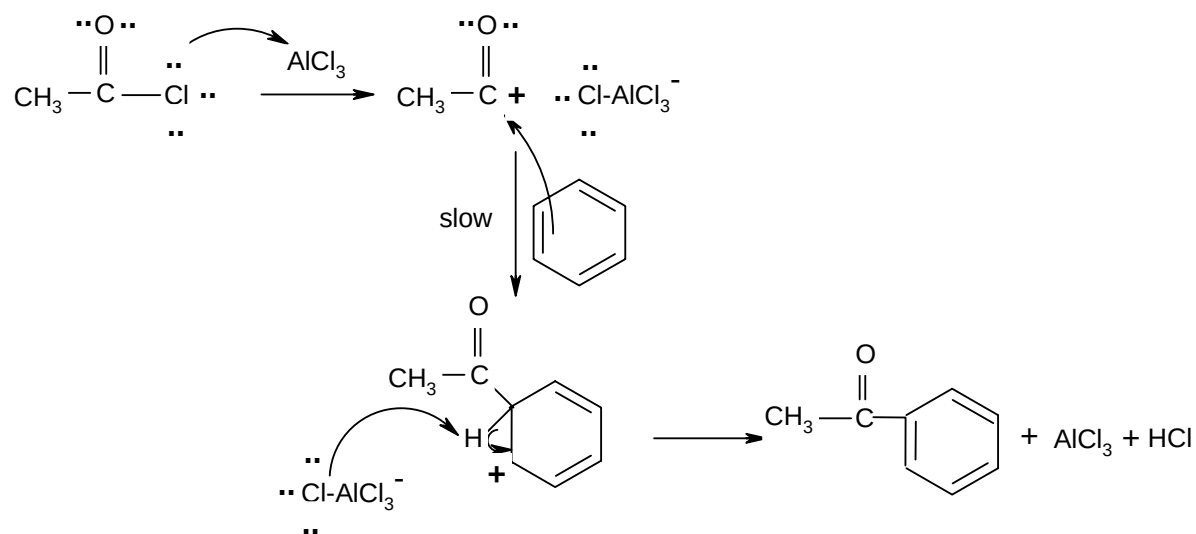
i) The nucleophilic substitution in acid anhydrides involves cleavage of C-O bond between central oxygen and one of the carbonyl groups. The result is that one acyl group is transferred to an attacking nucleophile; whereas, the other acyl group retains its single bond to oxygen and becomes the acyl group of a carboxylic acid



In Friedel crafts acylation, reactions an acyl cation is formed as an intermediate.



Mechanism of Friedel crafts acylation



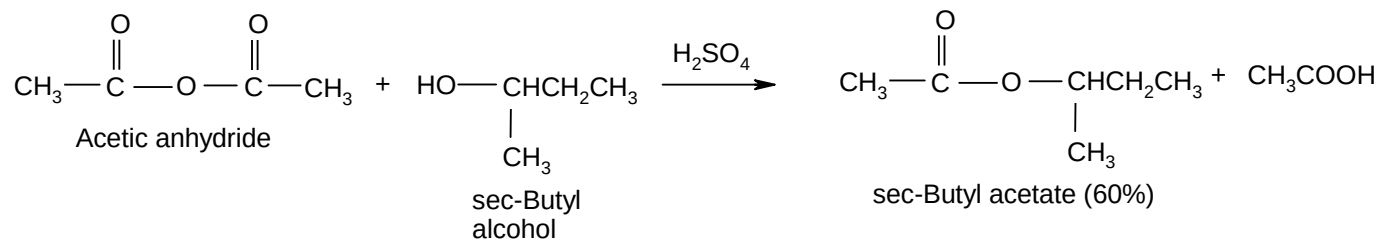
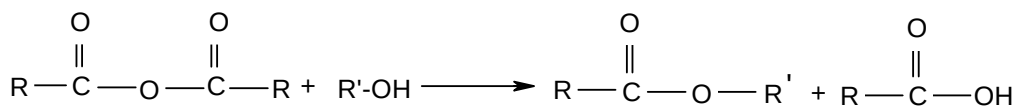
Step 1. The acyl halide reacts with lewis acid to form acylium ion a more electrophilic carbon.

Step 2. The pi electrons of the aromatic C=C acts as a nucleophile, attacking the electrophilic C⁺.

Step 3. Removal of the proton from the sp³ carbon bearing the acyl group reforms the C=C and the aromatic system, generating HCl and regenerating the active catalyst AlCl₃.

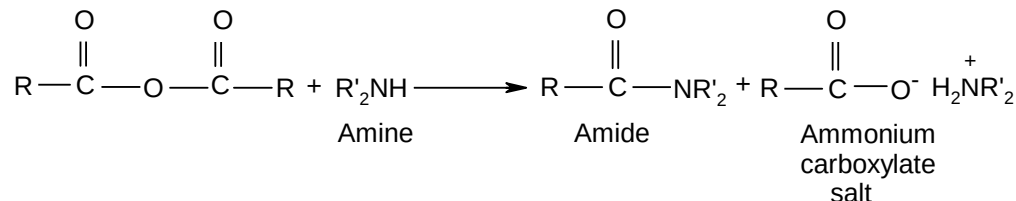
i) Reaction with alcohols

The reaction of acid anhydrides with alcohols leads to the formation of esters. The reaction is usually carried out in the presence of pyridine and may be catalyzed by small amount of acids. An acyl group of acetic anhydride is incorporated into the ester whereas the other becomes the acyl group of an acetic acid molecule.



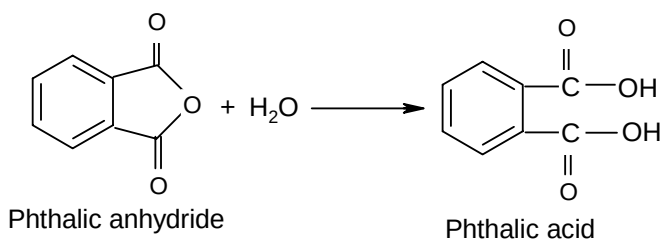
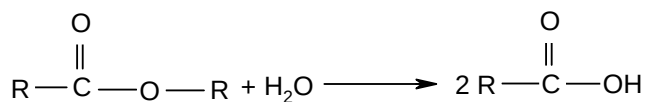
ii) Reaction with ammonia and amines

The reaction of acid anhydrides with ammonia or amines gives amides. However, the reaction requires two mole equivalents of amine. One of the acyl groups of acetic anhydride is incorporated into the amide whereas the other becomes the acyl group of the amine salt of acetic acid as shown below-



iii) Hydrolysis

Acid anhydrides on reaction with water yields two moles of a carboxylic acid. On the other hand cyclic anhydrides on hydrolysis give dicarboxylic acids.



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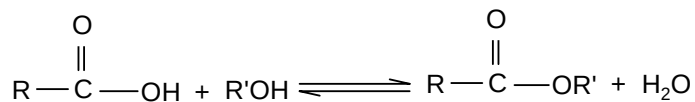
1. Preparation

Many esters have been found to occur in nature. The low molecular weight esters are fairly volatile, and possess pleasing odors. The presence of esters can be easily detected by their smell and they form a significant fraction of the fragrant oils of fruits and flowers.

Esters can be prepared using the following reactions:

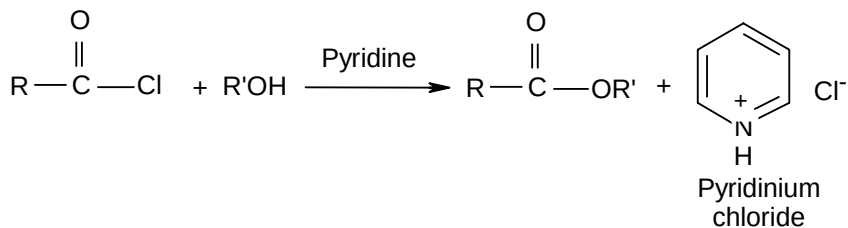
i) From carboxylic acids

Alcohols and carboxylic acids react in the presence of an acid catalyst to form an ester and water. This reaction is called as the Fischer esterification. The reaction follows $A_{AC}2$ mechanism as reported earlier in chemical properties of carboxylic acids.



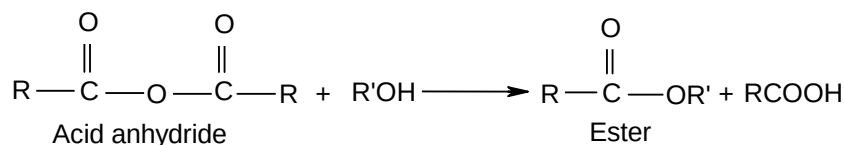
ii) From acyl chloride

The reaction of alcohols with acyl chlorides by nucleophilic acyl substitution yields esters. The reaction is carried out in the presence of a weak base such as pyridine.



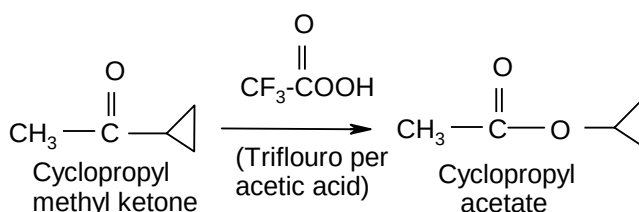
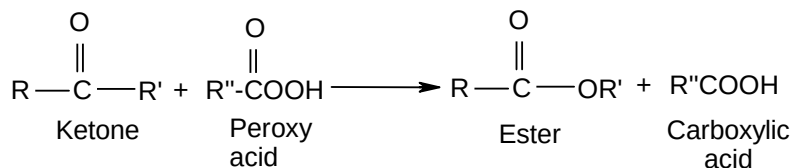
iii) From anhydrides of carboxylic acids

The transfer of an acyl group from an acid anhydride to an alcohol is a common method used for the preparation of esters. The reaction requires a catalyst, which is normally an acid (H_2SO_4) or base (pyridine).

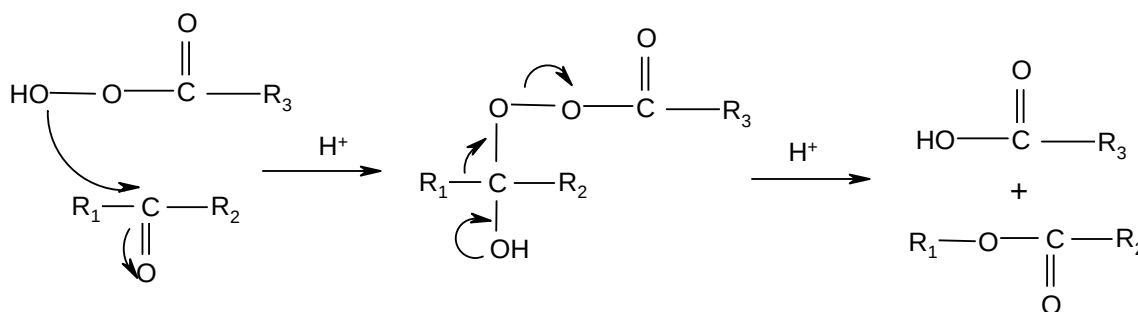


iv) Baeyer – Villiger oxidation

In Baeyer – Villiger oxidation ketones are converted to esters in presence of peroxy acids. The reaction proceeds by the migration of the group R' from carbon to oxygen. It is always the highly substituted group that migrates to oxygen. For example methyl ketones on treatment with peroxy acids give acetate esters.



Mechanism



2. Physical properties

Esters involve in hydrogen bonds as hydrogen-bond acceptors, but cannot act as hydrogen-bond donors, unlike their parent alcohols. This ability to participate in hydrogen bonding makes them more water soluble than their parent hydrocarbons. However, the limitations on their hydrogen bonding also make them more hydrophobic than either their parent alcohols or parent acids. Their lack of hydrogen bond donating ability means that ester molecule cannot hydrogen-bond to each other, which makes esters generally more volatile than an carboxylic acid of similar molecular weight.

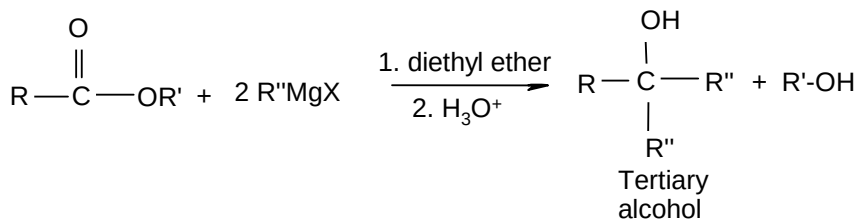
The small esters have boiling points, which are similar to those of aldehydes and ketones with the same number of carbon atoms. They are polar molecules like aldehydes and ketones having dipole-dipole attractions as well as vander waal dispersion forces.

The esters with low molecular weight are fairly soluble in water because cannot form hydrogen bond with themselves but they can hydrogen bond with water molecules.

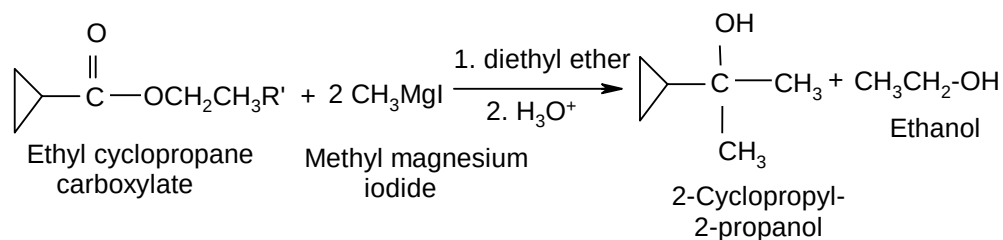
3. Chemical properties

i) Reaction with Grignard reagent

The reaction of esters with two equivalents of a Grignard reagent gives tertiary alcohols. In tertiary alcohols, two of the groups bonded to the carbon that bears the hydroxyl group are from the Grignard reagent.

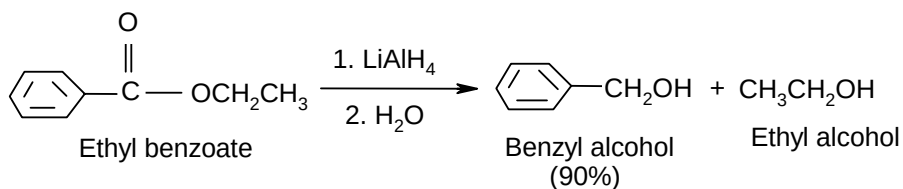
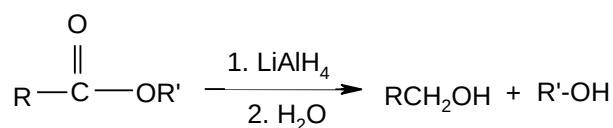


Two R'' groups are from Grignard reagent.



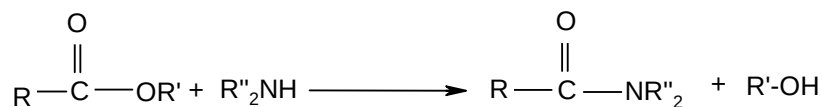
ii) Reduction with lithium aluminum hydride (LiAlH₄)

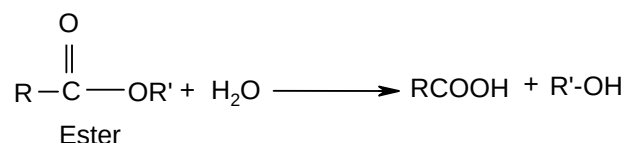
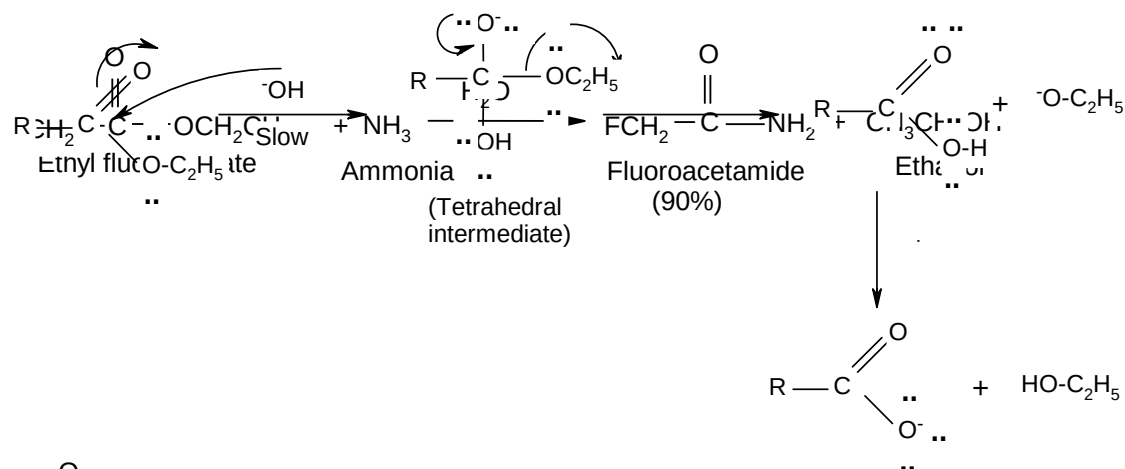
Esters on treatment with lithium aluminum hydride yield two alcohols.



ii) Reaction with ammonia and amines

Reaction of esters with ammonia/amines gives amides. Methyl and ethyl esters are very reactive and rapidly form amides.

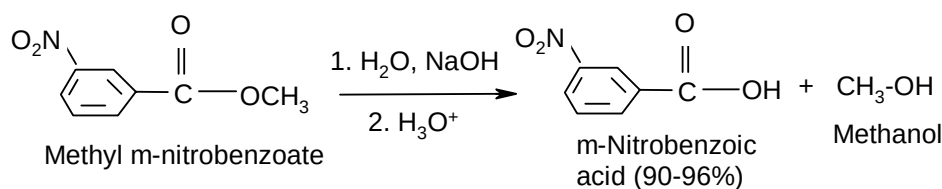




For example

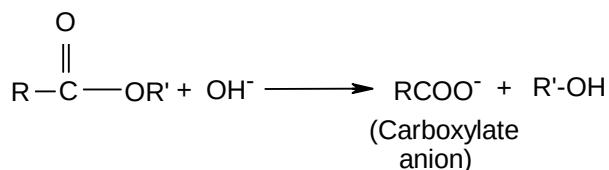
iii) Hydrolysis

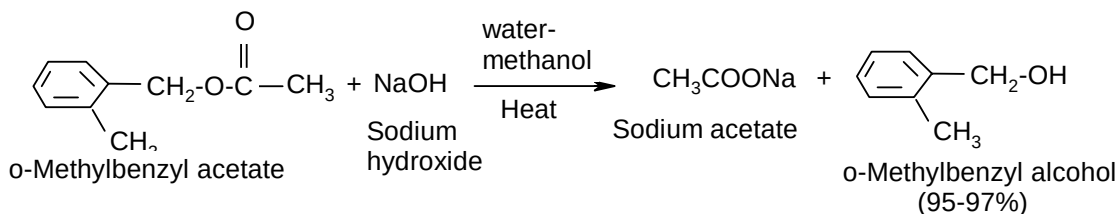
The hydrolysis of esters may be catalyzed either by using acids or by bases. Acid catalyzed hydrolysis is considered as the reverse of the Fischer esterification (A_{AL1}), whereas base catalyzed hydrolysis is irreversible (B_{AC2}). The base catalyzed hydrolysis is usually preferred for preparative purposes. The general reaction is



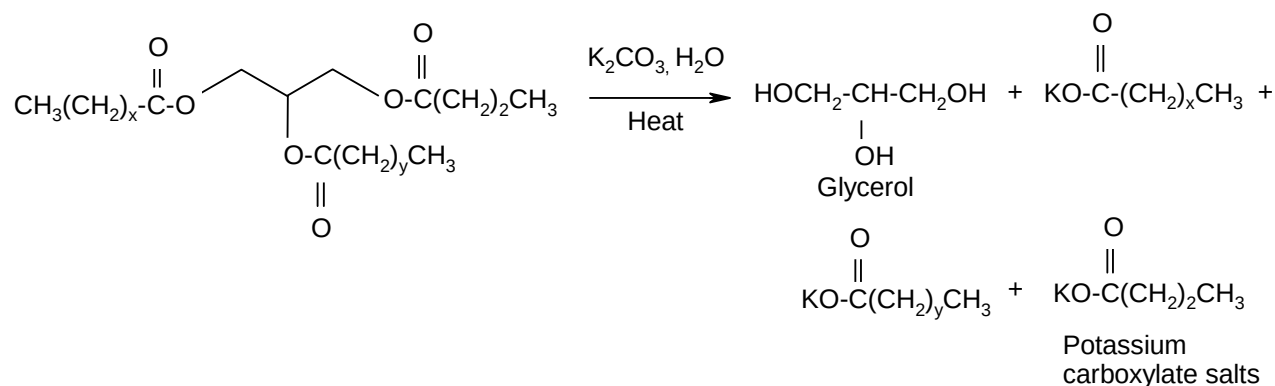
Mechanism

Unlike acid – catalyzed hydrolysis, which is equilibrium-controlled process, ester hydrolysis in aqueous base is usually irreversible. The reason is that carboxylic acids are converted to their corresponding anions, which are stable.





The hydrolysis of esters in basic medium is called as saponification; as it is used in soap making.



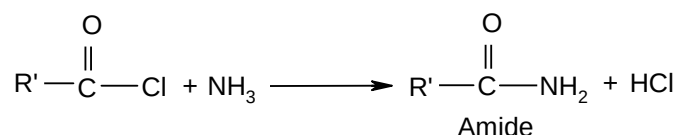
Potassium and sodium salts of long – chain carboxylic acids possess two ends. First a polar end having COO^- and a nonpolar, the hydrocarbon chain end. Thus, these compound form micelles in water that dissolve grease and have cleaning properties. The carboxylic acids obtained by the saponification of fats are called fatty acids.

Amides

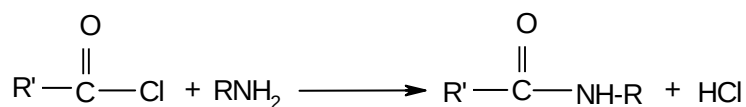
1. Preparation

Acid amides can be prepared by acylation of ammonia/amines with acyl chlorides, acid anhydrides or esters.

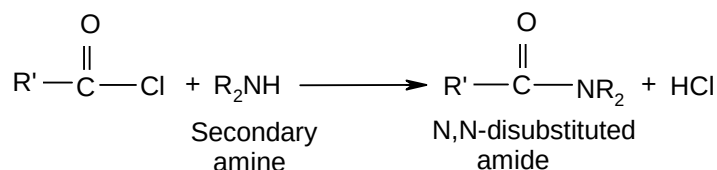
i) Acylation of ammonia



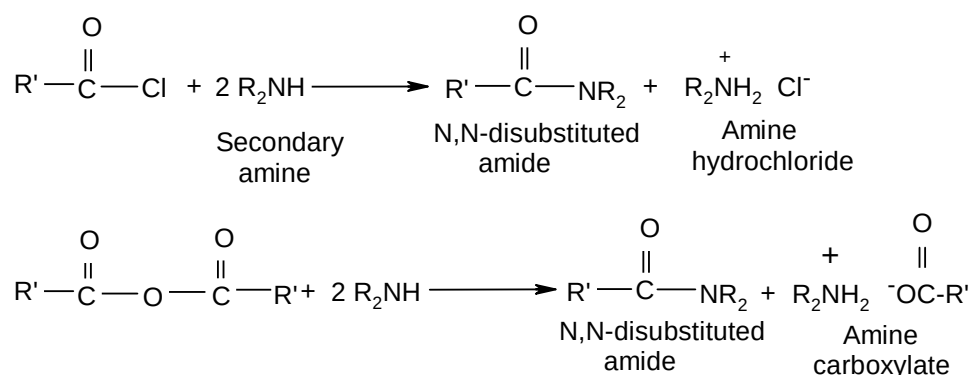
ii) Acylation of primary amines (RNH_2) yield N-substituted amides



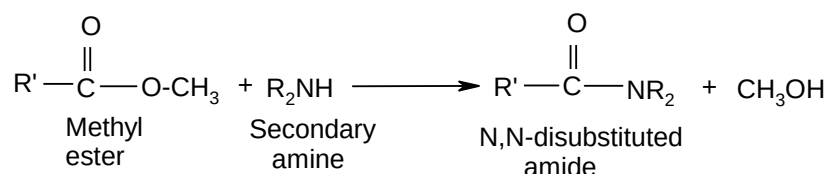
iii) Acylation of secondary amines (R_2NH) yield N,N-disubstituted amide



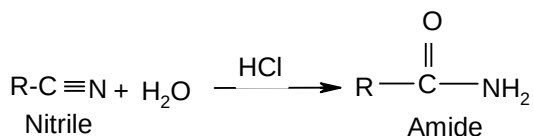
During acylation with acyl chlorides and acid anhydrides, two mole equivalents of amine are required in the reaction. One molecule of amine acts as a nucleophile, in the reaction and the second molecule acts as a bronsted base.



Amides can also be prepared by the reaction of esters and amines (1:1). In this reaction no acidic product is formed and hence no additional base is needed.



iv) The partial hydrolysis of nitriles also give amides as the product

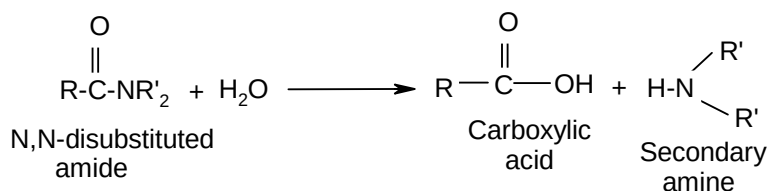


All amides are colourless crystalline solids. The lower amides (C₁ to C₄) are soluble in water.

2. Physical properties

Amide linkages in a biochemical context are called peptide linkages. Amide linkages constitute a defining molecular feature of proteins, the secondary structure of which is due in part to the hydrogen bonding abilities of amides.

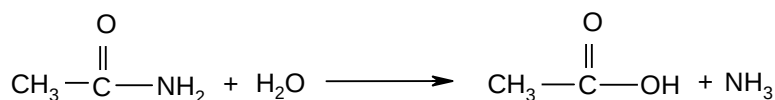
Amides are weaker base in comparison to amines. This is because of the presence of electron withdrawing carbonyl group in amides, where the lone pair of electron on the nitrogen is delocalized by resonance forming a partial double bond with the carbonyl carbon. On the other hand amides are stronger bases than carboxylic acids, esters, aldehydes and ketones.



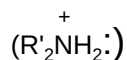
3. Chemical properties

i) Hydrolysis

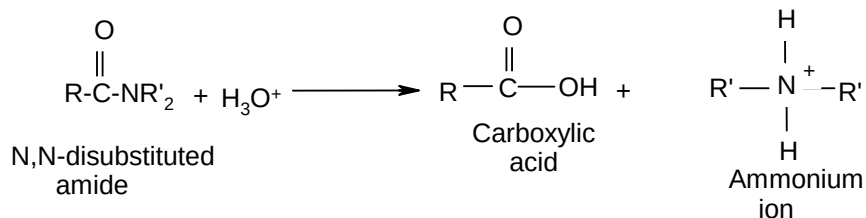
Amides are hydrolysed by acid, alkali and even by water. The hydrolysis by water is slow, by acid is rapid and by alkali is almost instant.



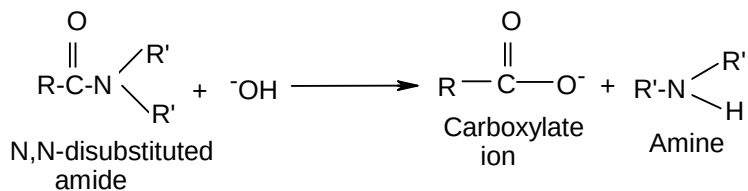
If hydrolysis is carried out in acidic medium, the amine formed is protonated giving an



ammonium ion,

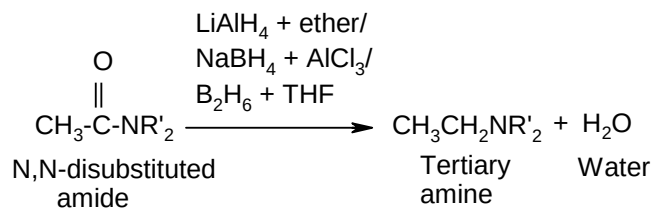
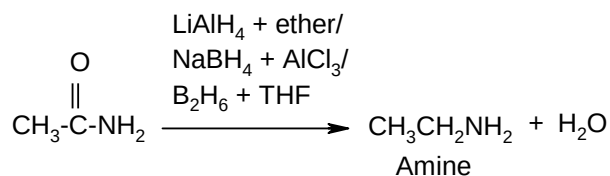


Whereas in basic medium, the carboxylic acid gets deprotonated, and a carboxylate ion is formed.



ii) Reduction

The reduction of amides with different reducing agents like LiAlH_4 in ether, NaBH_4 in AlCl_3 and B_2H_6 in THF give amines along with water. Thus $>\text{C}=\text{O}$ group is reduced to $-\text{CH}_2$.



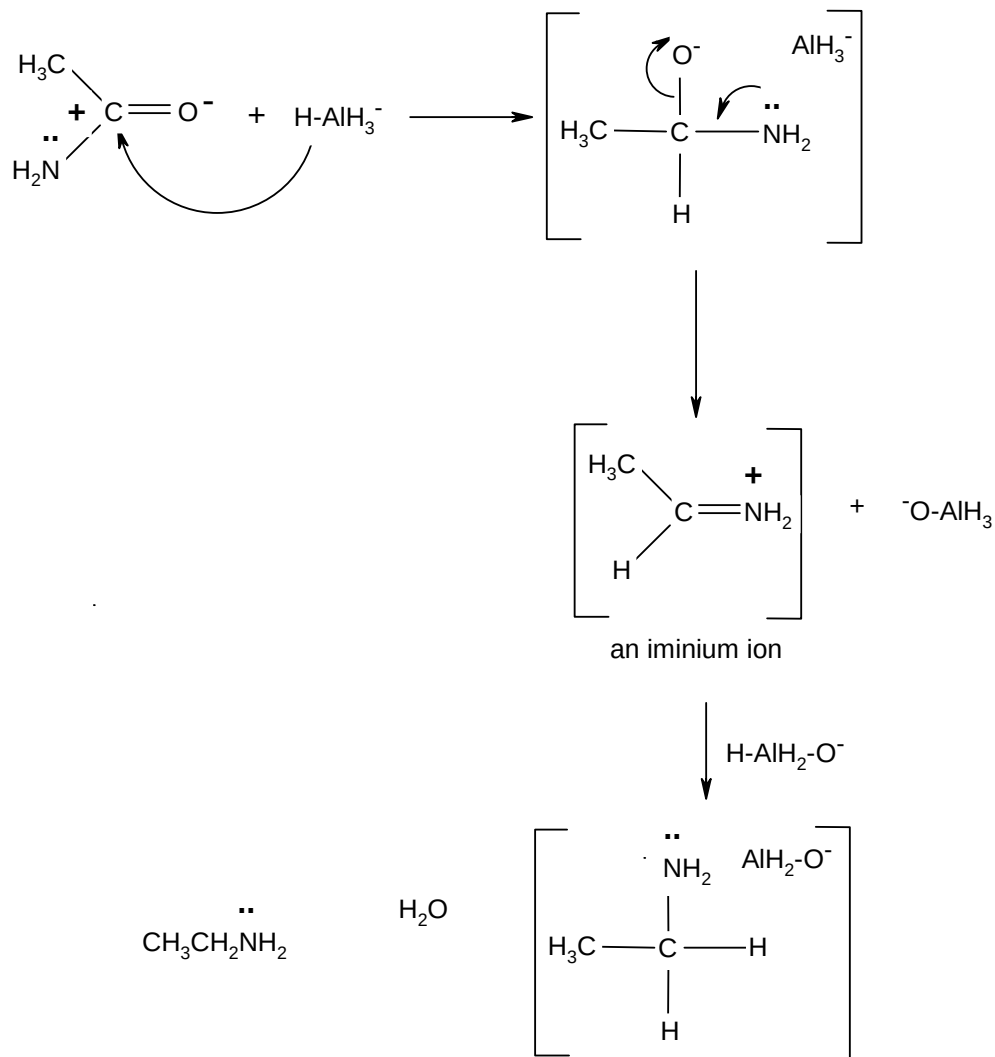
Mechanism

Step 1 attack of nucleophile on the carbonyl carbon resulting in the formation of tetrahedral intermediate.

Step 2 rearrangements of electron pair along with removal of carbonyl oxygen producing an iminium ion.

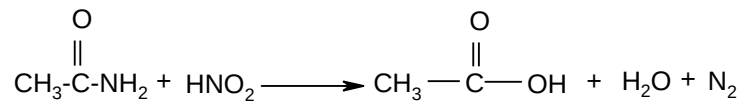
Step 3 attack of nucleophile to the double bonded carbon atom, which again produces a tetrahedral intermediate.

Step 4 hydrolysis of the intermediate formed resulting in the formation of amine.



iii) Reaction with HNO_2

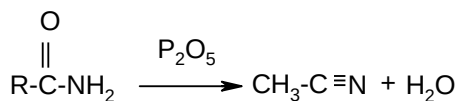
The treatment of amides with nitrous acid gives carboxylic acids along with nitrogen gas and water.



The nitrous acid required for the reaction is prepared by mixing sodium nitrite and dil HCl.

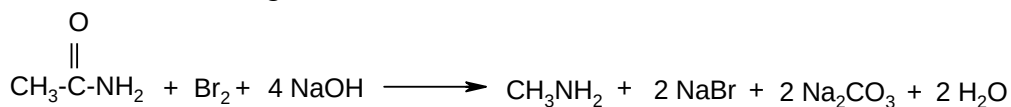
iv) Dehydration

Loss of water molecule occurs in presence of P_2O_5 and nitriles are produced.



v) Hofmann Bromamide reaction

Hofmann Bromamide reaction is a characteristic reaction of amides in which amide with NaOH/KOH in presence of bromine are used. The product is an amine having one less carbon atom than the starting amide.



This reaction is utilized for the conversion of amides to amines having one carbon atom less.

Mechanism

Step 1 attack of base (OH^-) facilitating dehydration of amide.

Step 2 attack of Br to the double bonded nitrogen resulting in the formation of an N-bromoamide.

Step 3 rearrangements of electron pair helps in releasing Br^- and producing an isocyanate.

Step 4 hydrolysis of an isocyanate resulting in an unstable carbamic acid.

Step 5 carbamic acid decarboxylates to primary amine.

