Phenols

Ar-OH

•Phenols are compounds with an –OH group attached to an aromatic carbon.

•Although they share the same functional group with alcohols, where the –OH group is attached to an aliphatic carbon, the chemistry of phenols is very different from that of alcohols.



Nomenclature of Phenols

Phenols are usually named as substituted phenols. The methylphenols are given the special name, cresols. Some other phenols are named as hydroxy compounds.



Nomenclature of Phenols



named on basis of phenol as parent
substituents listed in alphabetical order
lowest numerical sequence: first point of difference rule

Nomenclature of Hydroxyphenols



1,2-Benzenediol

(common name: pyrocatechol)

1,3-Benzenediol

(common name: resorcinol)

1,4-Benzenediol

(common name: hydroquinone)

Nomenclature of Hydroxyphenols



p-Hydroxybenzoic acid

name on basis of benzoic acid as parent higher oxidation states of carbon outrank hydroxyl group

Structure of Phenol



phenol is planar

C—O bond distance is 136 ⁰A, which is slightly shorter than that of CH₃OH (142 ⁰A)

Hydrogen Bonding in Phenol



The hydroxyl group of phenols allows hydrogen bonding to other phenol molecules and to water.

Physical Properties of Phenol

Compared to compounds of similar size and molecular weight, hydrogen bonding in phenol raises its melting point, boiling point, and solubility in water.

Physical Properties of Phenol

	$C_6H_5CH_3$	C ₆ H₅OH	C_6H_5F
Molecular weight	92	94	96
Melting point (°C)	-95	43	-41
Boiling point (°C,1 atm)	111	132	85
Solubility in H ₂ O (q/100 mL.25°C)	0.05	8.2	0.2

Acidity of Phenols

- Phenols (pK_a ~10) are much more acidic than alcohols (pK_a ~ 16) due to resonance stabilization of the phenoxide ion
- Phenols react with NaOH solutions (but alcohols do not), forming soluble salts that are soluble in dilute aqueous
- A phenolic component can be separated from an organic solution by extraction into basic aqueous solution and is isolated after acid is added to the solution

Comparative Acidity of Phenol



The Phenoxide Anion is Stabilized Through Resonance



Phenols are Converted to Phenoxide Ions in Aqueous Base



Electron-Releasing Substituents have Little Effect on the pKa of Phenols



Electron-Withdrawing Substituents Lower the pKa of Phenols



Effect of substituent groups on acid strength



Electron withdrawing groups will decrease the negative charge in the phenoxide, lowering the PE, decreasing the ΔH , shifting the equil farther to the right, stronger acid.

Electron donating groups will increase the negative charge in the phenoxide, increasing the PE, increasing the Δ H, shifting the equilibrium to the left, weaker acid.

Effect of Electron-Withdrawing Groups is Most Pronounced at Ortho and Para Positions



Direct Conjugation of the Negatively Charged Group with the Nitro Substituents is Possible



Consequence? Electron-withdrawing substituents (inc. NO₂) have larger effect on the pKa of a phenol group when in an *ortho* or *para* relationship

Direct Conjugation of the Negatively Charged Group with the Nitro Substituents is not Possible



Consequence? Electron-withdrawing substituents (inc. NO_2) have a smaller effect on the pKa of a phenol group when in a *meta* relationship

The Effect of Electron-Withdrawing Substituents on pKa of Phenols is Cumulative



pK_a 7.2

pK_a 4.0





Industrial Preparation of Phenol



Preparation of Phenol from Diazonium Salts



Remember - reaction proceeds via aryl cation

Preparation of Phenol from Cumene

Forms cumene hydroperoxide with oxygen at high temperature



Laboratory Preparation of Phenol

From aromatic sulfonic acids by melting with NaOH at high temperature Limited to the preparation of alkyl-substituted phenols



Electrophilic Aromatic Substitution in Phenols

Halogenation Nitration Nitrosation Sulfonation **Friedel-Crafts Alkylation Friedel-Crafts Acylation**

Electrophilic Aromatic Substitution



Sigma Complex or Wheland Intermediate

OH groups on benzene rings are ortho, para-directing and strongly activating

Halogenation of Phenols

- Phenols react with halogens to yield mono-, di-, or tri-substituted products, depending on reaction conditions.
 - For example, an aqueous bromine solution brominates all ortho and para positions on the ring.



Halogenation of Phenols

 Likewise, you can accomplish monobromination by running the reaction at extremely low temperatures in carbon disulfide solvent.



Halogenation of Phenols - Non-Polar Solvents



monohalogenation occurs in non-polar solvents (1,2-dichloroethane)

Halogenation of Phenols - Polar Solvents



multiple halogenation in polar solvent (water)

 Phenol, when treated with dilute nitric acid at room temperature, forms ortho- and para-nitrophenol.



 Phenol, when treated with concentrated nitric acid at and Conc. Sulphuric acid room temperature, forms trinitrophenol.





Active Electrophile



OH the group is more electron donating than the methyl and group consequently controls the regiochemistry this of reaction



Hydroxyl groups are *ortho, para*-directing, while carboxylate groups are *meta*-directing. In this example, these effects reinforce each other and a single product is obtained



Active Electrophile

only strongly activated rings undergo nitrosation when treated with nitrous acid

Sulfonation of Phenols

 The reaction of phenol with concentrated sulfuric acid is thermodynamically controlled. At 25°C, the ortho product predominates while at 100°C, the para product is the major product.


Sulfonation of Phenols





Step 1:

-The alkyl halide reacts with the Lewis acid to form a a more electrophilic C, a carbocation

Step 2:

-The p electrons of the aromatic **C=C** act as a nucleophile, attacking the electrophilic C+. This step destroys the aromaticity giving the cyclohexadienyl cation intermediate.

Step 3:

-Removal of the proton from the sp3 C bearing the alkyl- group reforms the **C=C** and the aromatic system, generating HCI and regenerating the active catalyst.





Acylation of phenolic compounds can take place either on the ring by electrophilic aromatic substitution or on oxygen by nucleophilic acyl substitution

Friedel-Crafts Conditions Yield Aryl Ketones via C-Acylation



'Unactivated' Acylating Reagents Provide Aryl Esters via O-Acylation



in the absence of AICl₃, acylation of the hydroxyl group occurs (O-acylation)

O-Acylation vs. C-Acylation



O-Acylation is kinetically controlled process; C-acylation is thermodynamically controlled

AICI₃ catalyzes the conversion of the aryl ester to the aryl alkyl ketones; this is called the Fries rearrangement

Fries Rearrangement

When esters of phenol are heated with anhydrous AlCl₃, the acyl group migrates from the phenolic oxygen to an *ortho*-or *para*- position on the ring, thus yielding a ketone. This reaction of conversion of phenolic esters to acylated phenols in presence of a lewis acid or a catalyst is known as Fries rearrangement, *e.g.*,



Fries Rearrangement

- The ortholpara ratio is largely dependent on the reaction temperature, solvents used and on the catalyst concentration. Low temperature (60 °C or less) favours *p*-isomer whereas high temperature (above 160 °C) favours *o*-isomer. The *para*product is appeared to be kinetically controlled, whereas the ortho-product is thermodynamically controlled. Perhaps, owing to steric hindrance, the ortho-isomer can't be formed at a low temperatures.
- The mechanism of Fries rearrangement is a matter of much controversy .Several mechanisms has been proposed but the exact mechanism is still not completely worked out. The most common mechanism was given by Ogata and Tabuchi. They suggest an intramolecular migration of acetyl group to both *ortho-* and *para-* positions, involving a normal –complex intermediate.

Mechanism of Fries Rearrangement



Mechanism of Fries Rearrangement



Alkylation

Sodium phenoxide when treated with alkyl halides forms phenolic ethers.

For methyl ether, methyl sulfate $(CH_3)_2SO_4$, may be used.



Alkylation

This method resembles Williamson's synthesis for preparing ether. Mixed ether can also be obtained by passing the mixed vapours of phenol and some alcohol over heated alumina.



Acylation

Phenol reacts with acid chlorides and acid anhydrides to form corresponding ethers. The hydrogen atom of the hydroxyl group is replaced by the corresponding acyl group (RCO-).
The reaction with benzoyl chloride is called Schotten Baumann's reaction



Reimer-Tiemann Reaction



The salicylaldehyde can be easily oxidized to salicylic acid

Reimer-Tiemann Reaction

•When heated with chloroform and caustic alkali, phenol gives ohydroxybenzaldehyde (salicylaldehyde).

•A substituted benzal chloride is initially formed which gets hydrolysed by the alkaline reaction medium.



Reimer-Tiemann Reaction

When heated with carbontetrachloride and caustic alkali, phenol gives ohydroxybenzoic acid (salicylic acid)



Mechanism of Reimer-Tiemann Reaction

The reaction involves the formation of an electron deficient reactive species **dichlorocarbene** by the action of alkali on chloroform, which is attack by the electron rich *ortho*-position of the phenoxide ring to form *ortho*-dichloromethylphenolate, which on hydrolysis yields the final product.

$$\overbrace{OH}^{CH} H \xrightarrow{CI}_{CI} \xleftarrow{CI}_{CI} \xrightarrow{-CI}_{CI} \xrightarrow{-CI}_{CI_2}$$

Mechanism of Reimer-Tiemann Reaction



Kolbe-Schmitt Reaction (carbonation)

When sodium salt of phenol is heated with carbondioxide at 120-140 °C under pressure (6-7 atmospheres) sodium salicylate is produced. This on further treatment with HCl yields salicylic acid.



Mechanism of Kolbe-Schmitt Reaction

Note the high charge density at the C-2, C-4 and C-6 positions of the phenoxide anion

The alkoxide group is a strongly activating *ortho, para*-directing group



Mechanism of Kolbe-Schmitt Reaction

Mechanism of Ortho Carboxylation



Mechanism of Kolbe-Schmitt Reaction

Intramolecular Hydrogen Bonding in Salicylate Ion



Hydrogen bonding between carboxylate and hydroxyl group stabilizes salicylate ion. Salicylate is less basic than *para* isomer and predominates under conditions of thermodynamic control.

Lederer-Manasse Reaction

Phenol readily condenses with formaldehyde (formalin 40% aqueous solution) at low temperature and in the presence of dilute acid or alkali. The main product is *p*-hydroxybenzyl alcohol and a small amount of *o*-isomer



Lederer-Manasse Reaction

With larger quatities of HCHO, bis-hydroxymethyl phenol and p,p'-dihydroxydiphenylmethane are obtained.



Lederer-Manasse Reaction

In presence of excess of formaldehyde, three dimensional polymer called'Bakelite' is formed.



Phenol-Formaldehyde Resins



Houben–Hoesch Reaction

An organic reaction in which a nitrile reacts with an arene compound to form an aryl ketone. the reaction is a type of Friedel-Crafts acylation with hydrochloric acid and a Lewis acid catalyst.

Synthesis of acylphenols from phenols or phenolic ethers by the action of organic nitriles in the presence of hydrochloric acid and aluminum chloride as catalyst



Mechanism of Houben–Hoesch Reaction



Gattermann Reaction

When hydrogen cyanide is used, aromatic aldehyde may be obtained and the reaction is called **Gatterman reaction**.

Thus Gattermann reaction is a special case of the Hoesch reaction.



Condensation with Phthalic anhydride

When phenol is heated with phthalic anhydride in the presence of a little concentrated sulfuric acid, condensation takes place forming phenolphthalein.



Coupling with Diazonium Salts



Claisen Rearrangement of Aryl Allyl Ethers

The Claisen rearrangement is an example of pericyclic reactions, and belongs to the category of [3.3]-sigmatropic rearrangement.

It involves intramolecular thermal conversion of **allyl aryl** ethers to allylphenols.

The allyl group migrates from the ethereal oxygen to the ring carbon *ortho* to it. When both the *ortho*-positions are blocked, migration occurs at the respective *para*-position.



Mechanism of Claisen Rearrangement



Mechanism of Claisen Rearrangement

During ortho-migration the allyl group always undergoes an allylic shiftthe carbon alpha to the ethereal oxygen atom in the substrate becomes gamma to the ring in the product. However in *para*- migration, the allylic group is found exactly as it was in the starting ether.



Mechanism of Claisen Rearrangement

The Claisen rearrangement follows the first order kinetics. The rearrangement is strictly intramolecular and the mechanism is a concerted pericyclic [3,3]-sigmatropic shift. The reaction proceeds through a cyclic six-membered transition state in which the rupture of the oxygen-allyl bond is synchronous with the formation of a carbon-carbon bond at an *ortho*-position.


Mechanism of Claisen Rearrangement



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Sigmatropic Rearrangement

The Claisen rearrangement is an example of a sigmatropic rearrangement. A sigma (σ) bond migrates from one end of a conjugated π electron system to the other.

this α bond breaks

during reaction

"conjugated π electron system" is the allyl group

this α bond forms during reaction

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