Aromatics

The streets of London at the beginning of the Nineteenth Century were lit by gas lamps. The fuel was water gas, a mixture of carbon monoxide and hydrogen produced by heating coal with steam. This process also produces a sticky residue known as coal tar. The presence of a pungent, clear liquid in the gas lines led to the discovery of benzene in 1826 by Michael Faraday.

Benzene has the formula C_6H_6. It is rather unreactive chemically; for example, it does not react directly with chlorine or bromine. Benzene will react with bromine in the presence of a suitable catalyst such as iron bromide. The reaction is a substitution reaction producing bromobenzene and HBr.

$$C_6H_6 + Br_2 \xrightarrow{FeBr_3} C_6H_5Br + HBr$$

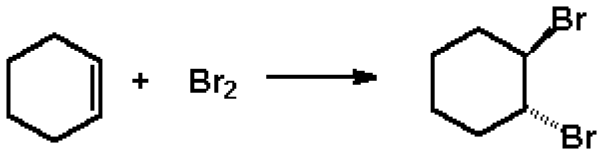
These properties made benzene a puzzle for chemists. The formula indicated that benzene must contain some combination of four rings and/or pi bonds. Consider the following formulas:

Comparison of the formulas of C_6 Hydrocarbons

Compound	Formula
Benzene	C_6H_6
Hexane	C_6H_{14}
cyclohexane or hexene	C_6H_{12}
cyclohexene or hexyne	C_6H_{10}

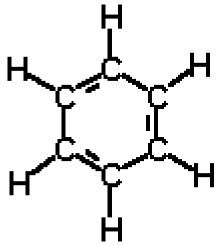
We have seen that alkenes and alkynes react with bromine by an addition mechanism. Consider the rapid, uncatalyzed addition of bromine to cylohexene .

$$C_6H_{10} + Br_2 \longrightarrow C_6H_{10}Br_2$$

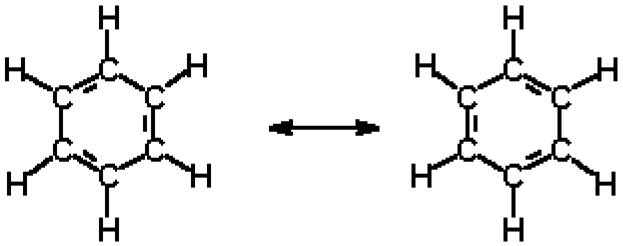


Structure of Benzene

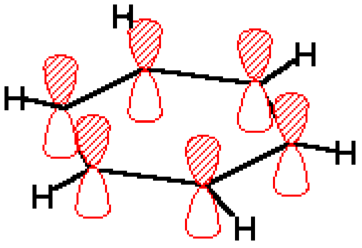
For forty years after its discovery, chemists puzzled over the structure of benzene. Since one theory of bonding popular at the time ruled out the existence of cyclic structures, and double bonds were not recognized until 1859, the problem of assembling six carbons and six hydrogens was formidable indeed. In 1866 Friedrich Kekulé proposed a cyclic structure with alternate single and double bonds.

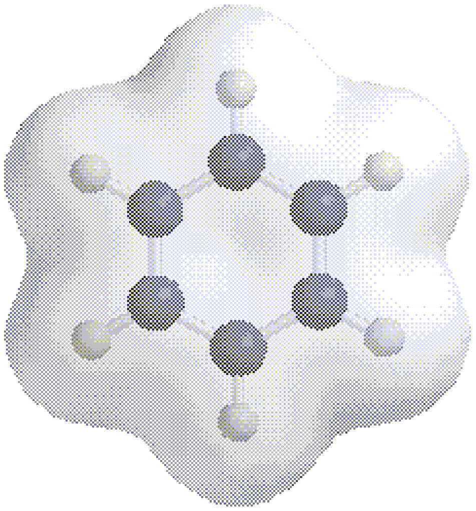


This structure had some difficulties, however. We know that single bonds are longer than double bonds, but spectroscopic measurements show that benzene is planar and has equal C-C bonds lengths that are intermediate between single and double bonds. In the 1930s, Linus Pauling and others developed resonance theory of bonding. According to this theory, the structure of benzene is not represented accurately by either of the two Kekulé structures, but is a hybrid between them. It is important to remember that the double headed arrow indicates resonance contributors to the total structure and is not an equilibrium. Benzene does not oscillate between the two structures, the double bonds acting like windshield wipers. Each of the six carbon atoms in benzene is sp^2 hybridized. The six-membered ring is constructed of sigma bonds made of overlapping sp^2 bonds. The p orbitals on each carbon atom are aligned perpendicular to the ring and overlap. The six pi electrons are distributed uniformly around the ring.



Resonance contributors to benzene.



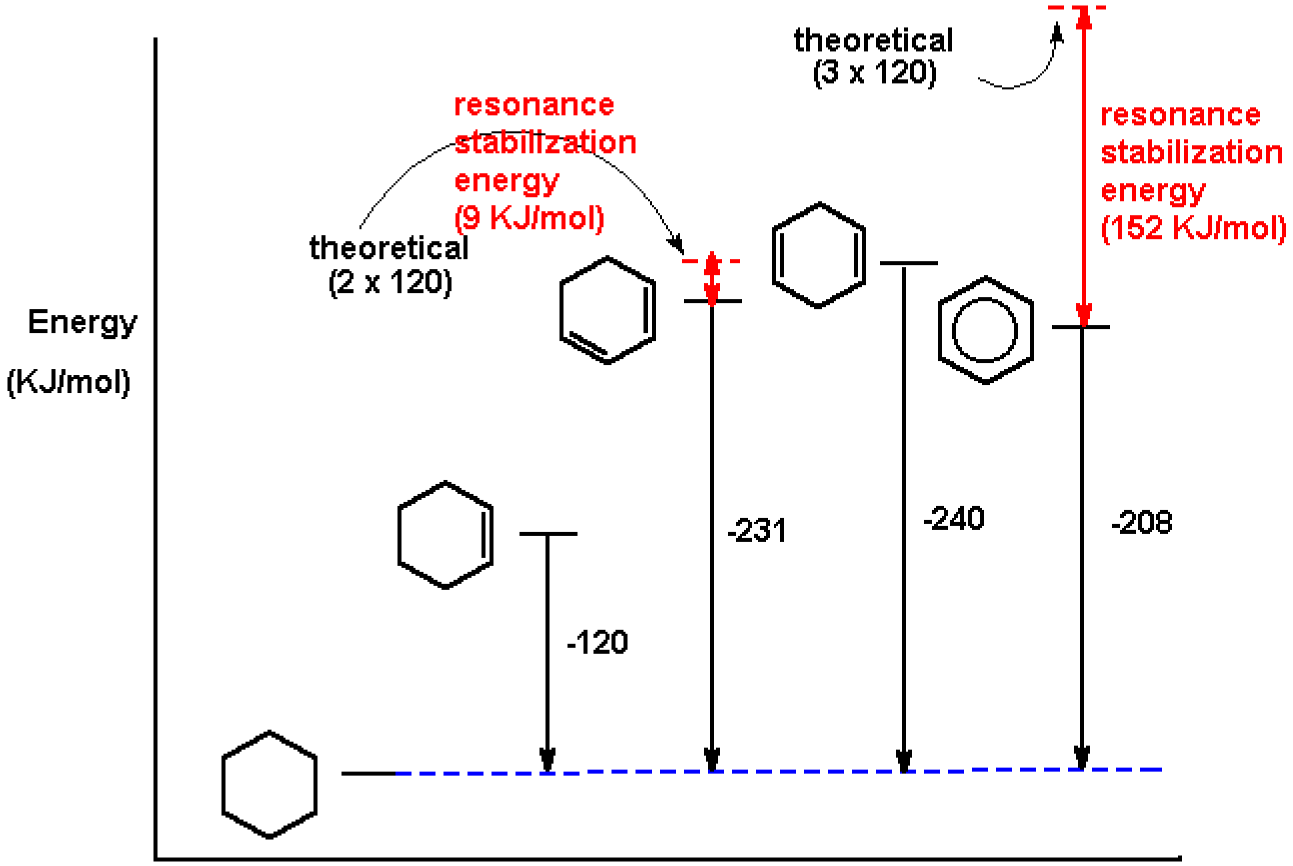


Molecular orbital representation of

Calculated electron density for benzene shown as a white surface superimposed on a ball&stick model to show the arrangement of atoms.

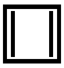
Stability of Benzene

The stability of benzene can be demonstrated by comparing the experimentally determined heats of hydrogenation of cyclohexenes. Benzene, cyclohexene, and cyclohexadiene all give cyclohexane upon catalytic hydrogenation. Hydrogenation of cyclohexene to cyclohexane releases 120 KJ/mol. Theoretically, reduction of cyclohexadiene should release 2 x 120 or 240 KJ/mol. This is the value obtained with 1,4-cyclohexadiene but is 8 KJ/mol more than the heat of hydrogenation of 1,3-cyclohexadiene. The difference is attributed to the delocalization of electrons in the conjugated diene system. Benzene, according to its Kekulé structure should have a heat of hydrogenation of 3 x 120 or 360 KJ/mol. The actual value of -208 KJ/mol reveals an energy difference of 152 KJ/mol! This is the resonance stabilization energy of benzene.

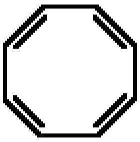


Aromaticity

What makes benzene so special in terms of its stability? The Kekulé structure with its alternate double and single bonds would suggest that other conjugated cyclic systems should be like benzene in terms of its stability. This is certainly not true! Cyclobutadiene (C_4H_4) appears to be similar to benzene, but is so highly reactive that it can only be prepared as individual molecules in the gas phase or trapped in an inert matrix. If two molecules of cyclobutadiene come into contact, they react rapidly.



1,3,5-Cyclooctriene (C_8H_8) was prepared by Richard Willstätter. He found that this compound underwent addition reactions with bromine just like normal alkenes and very much unlike benzene. Spectroscopic studies show cyclooctatiene is bent, not planar like benzene.



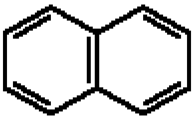
Hückel Rule for Aromaticity

A rule for determining if a compound is aromatic was derived by Erick Hückel. For a compound to be aromatic it must meet all of these criteria:

- planar cyclic system
- continuous overlap of p orbitals
- 4N + 2 pi electrons, where N is an integer. This corresponds to 2, 6, and 10 pi electrons for N = 0, 1, and 2.

Cyclobutadiene meets the first two criteria but has only 4 pi electrons so is not aromatic. 1,3,5-cyclooctatriene is not planar and contains 6 pi electrons and is not aromatic. Benzene with its 6 pi electrons meets all three criteria and is aromatic.

Hückel's rule also applies to polycyclic compounds. Naphthalene and azulene both have 10 continuous pi electrons in a planar molecule and are aromatic.



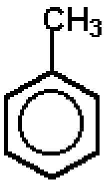
naphthalene

azulene

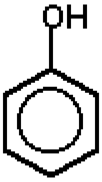
Nomenclature

Aromatic compounds have been important chemicals since the mid 1800's and many common names for these compounds are still widely used instead of their systematic IUPAC names.

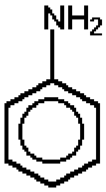
- Some common names for monosubstituted benzenes:



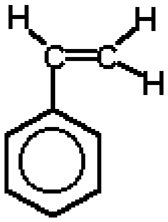
toluene



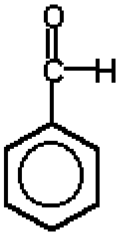
phenol



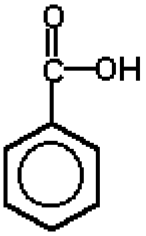
aniline



styrene

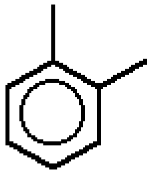
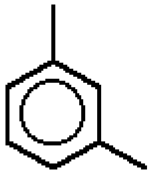
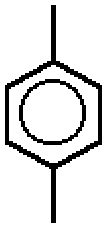


benzaldehyde

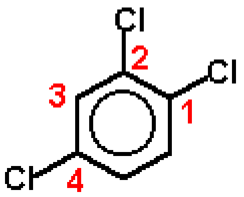


benzoic ac

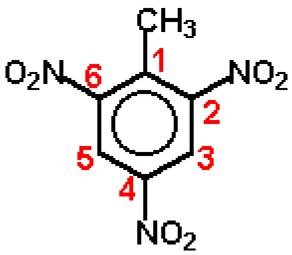
- Disubstituted benzenes are named by numbering the ring starting from the substituent that gives the parent name. The substitution pattern is specified by numbers or the prefizes ortho-, meta-, and para-.

Substitution	Common Prefix	Numbering
	1,2-	ortho- (o-)
	1,3-	meta- (m-)
	1,4-	para- (p-)

- If more than two substituents are present, the numbering system must be used. The ortho-, meta-, and para- designations apply only to disubstituted benzenes.



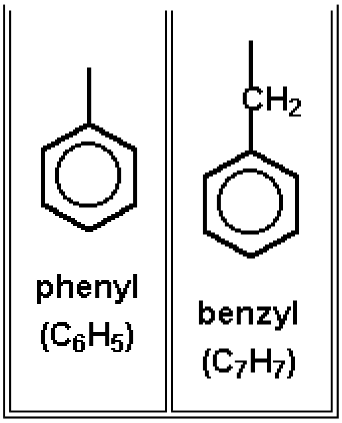
1,2,4-trichlorobenzene

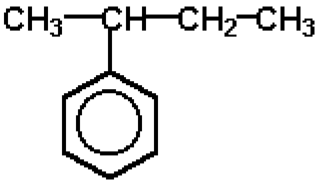


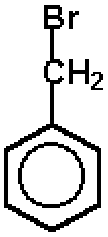
2,4,5-trinitrotoluene

(TNT the explosive)

- If the substituent does not have a simple name, the benzene ring may be named as a substituent. The two most common benzene substituents are:



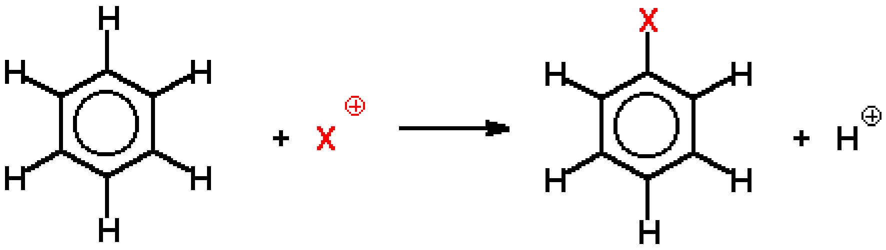

2-phenylbutane


benzyl bromide

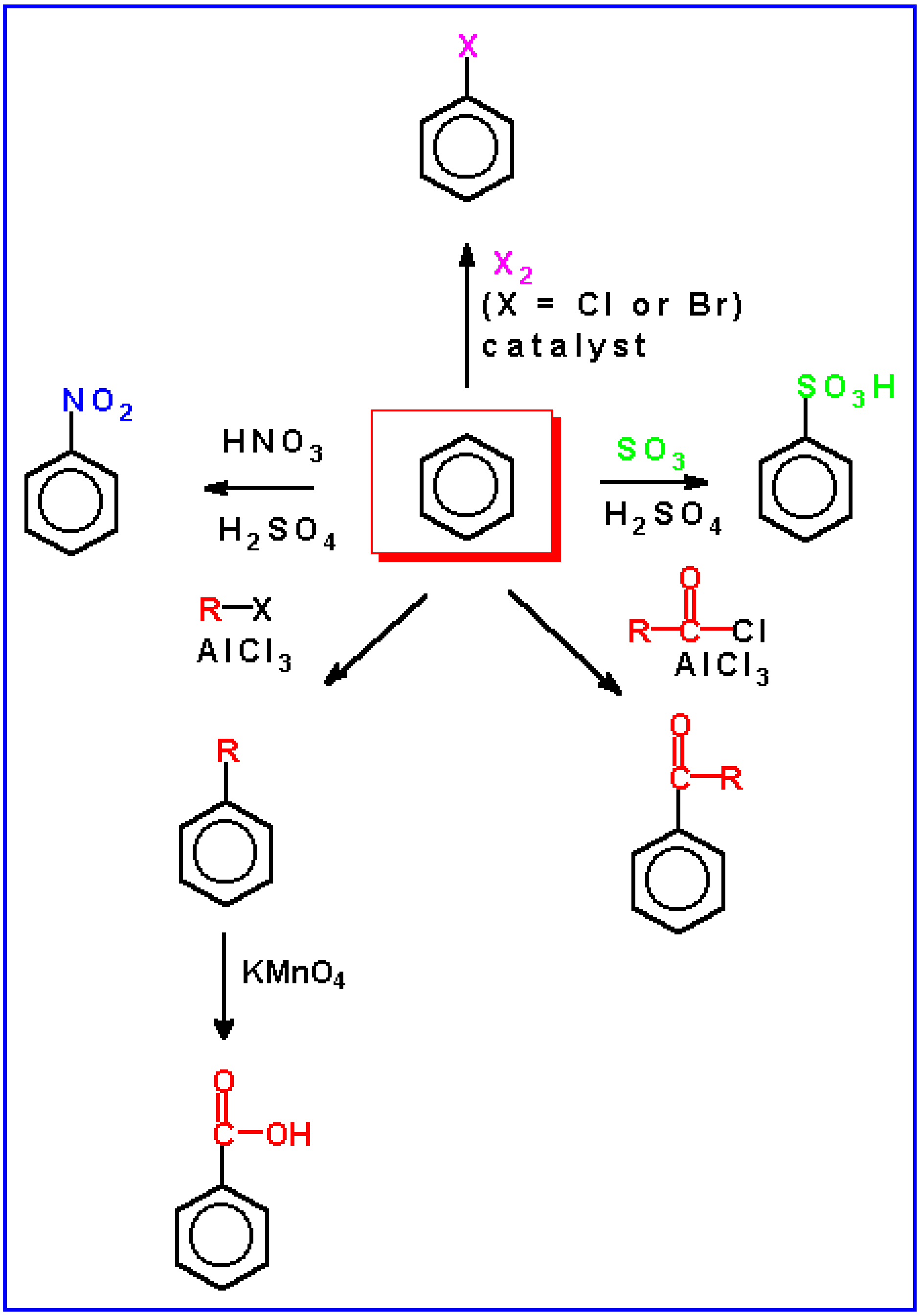
Chemistry of Benzene

Electrophilic Aromatic Substitution

The characteristic reaction of aromatic compounds is substitution of a hydrogen atom on the aromatic ring for an electrophile.

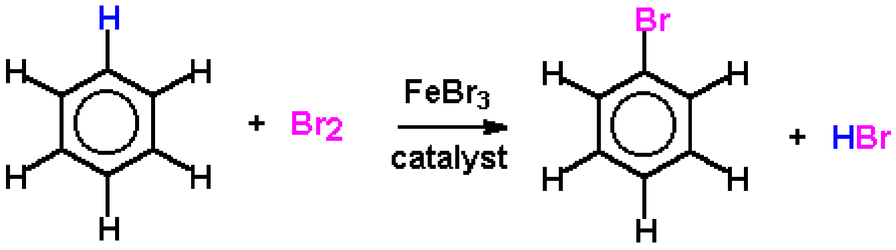


The following electrophilic aromatic substitution reactions are commonly used to prepare benzene derivatives. Clicking on a reaction will give further information.



Halogenation

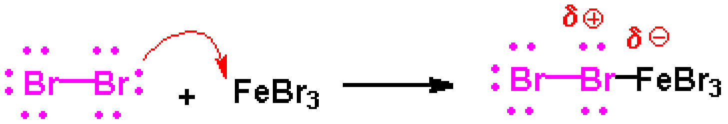
We have seen that the catalyzed bromination of benzene produces bromobenzene.



The mechanism for this reaction, and all other electrophilic substitution reactions, involves three steps.

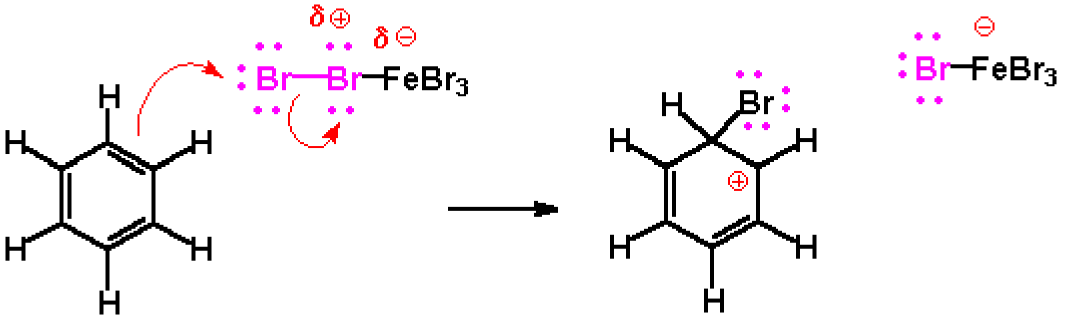
- Formation of an electrophile.

In this reaction bromine acts like a Lewis Base and $FeBr_3$ acts like a Lewis Acid. The resulting complex has a weak Br-Br bond which acts like Br^+, an electrophile.

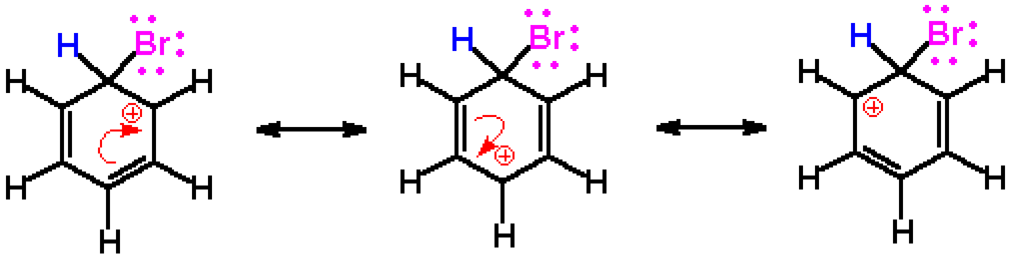


- Addition of the electrophile to the benzene ring.

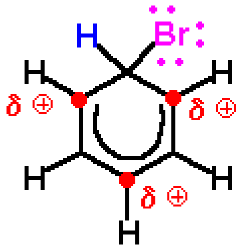
The pi electrons on the benzene ring are donated to the electrophile forming a cyclohexadienyl cation which is resonance stabilized. Note that the resonance stabilization results in the para and the two ortho carbon atoms sharing the positive charge.



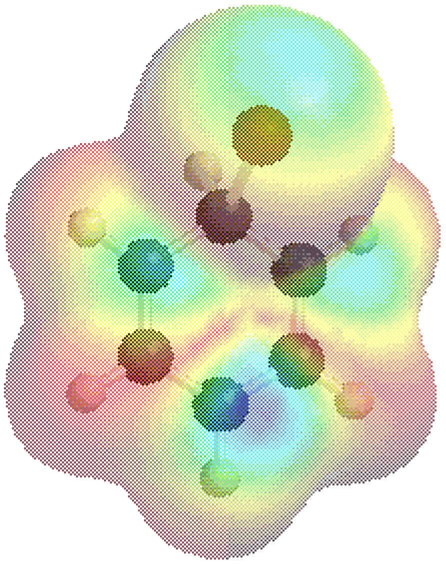
Resonance stabilization of intermediate cyclohexadienyl carbocation.



These resonance contributors show an intermediate with the positive charge delocalized among three carbon atoms.



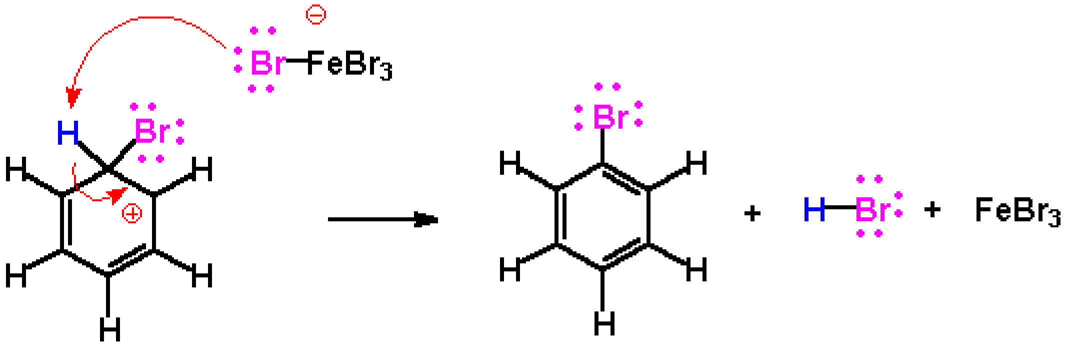
Sketch of the electron density of the bromobenzene intermediate.



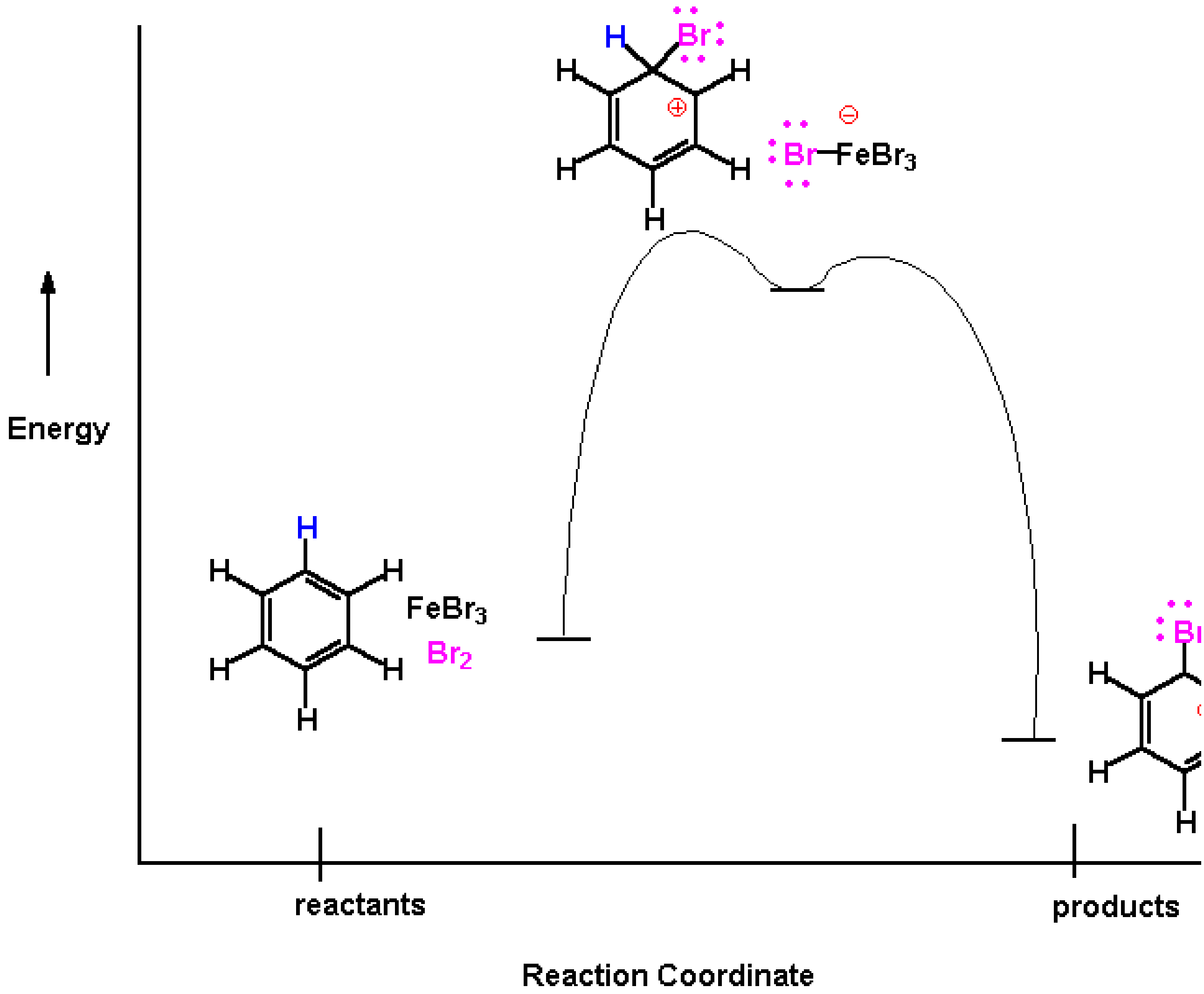
Computer generated image of the electron density of the bromobenzene intermediate. The purple and blue regions have the highest electron density.

- Elimination of H^+.

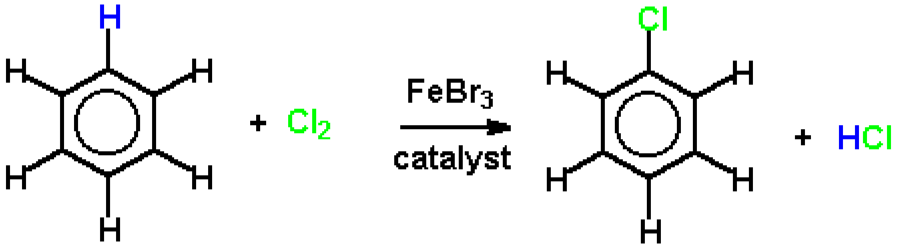
A nucleophile removes H^+ from the cyclohexadienyl cation restoring the stable aromatic ring and regenerating the $FeBr_3$ catalyst.



The mechanism can be described in a transition state diagram which shows the intermediate cyclohexadienyl carbocation.



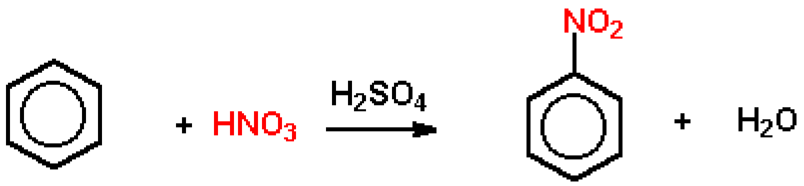
Chlorination of benzene proceeds in a similar manner using Cl_2 and $FeCl_3$ or $AlCl_3$ as a catalyst.



Elemental fluorine is too reactive to directly produce fluorobenzenes. These compounds must be prepared by direct routes.

Nitration

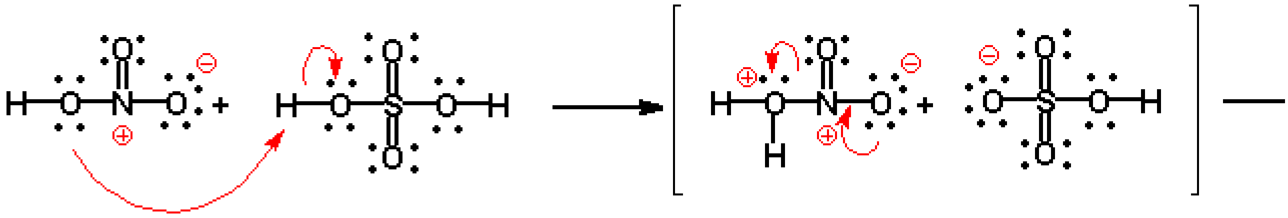
Nitro (NO_2) groups can be introduced onto a benzene ring using a mixture of nitric and sulfuric acid. The reaction follows the usual pattern:



- **Formation of the electrophile**

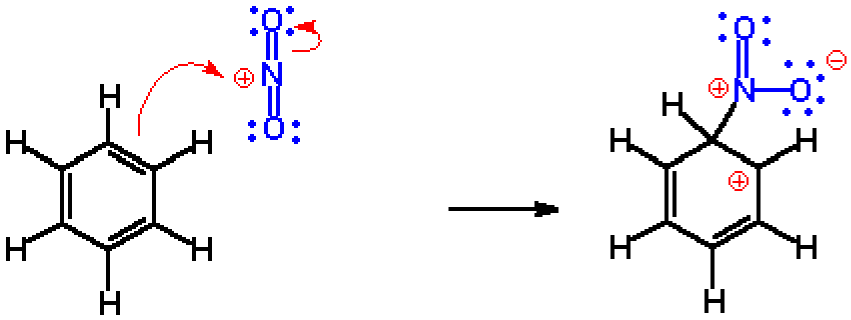
NO_2^+ is formed from acid catalyzed decomposition of HNO_3.

$$HNO_3 + H_2SO_4 \longrightarrow NO_2^+ + H_2O +$$

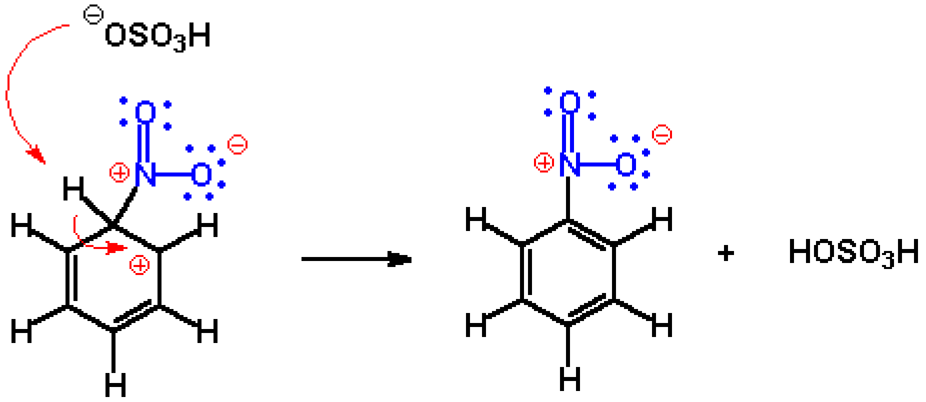


- **Addition of the electrophile to the benzene ring**

The electrophile adds to form the cyclohexadienyl carbocation destroying the aromaticity.

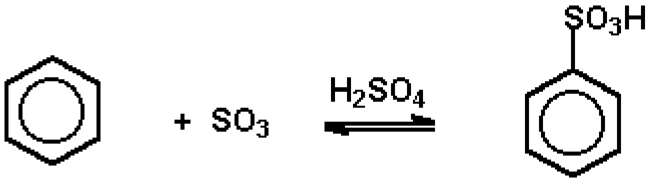


- **Elimination of H^+ to restore the aromatic ring**



Sulfonation

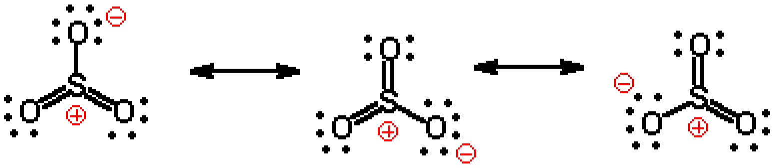
Sulfonic acid groups are introduced into benzene rings by the electrophile sulfur trioxide (SO_3) in sulfuric acid ("fuming sulfuric acid"). Sulfonation is unique among the electrophilic aromatic substitution reactions because it is reversible. Heating a sulfonic acid in dilute sulfuric acid removes the sulfonate group



Mechanism

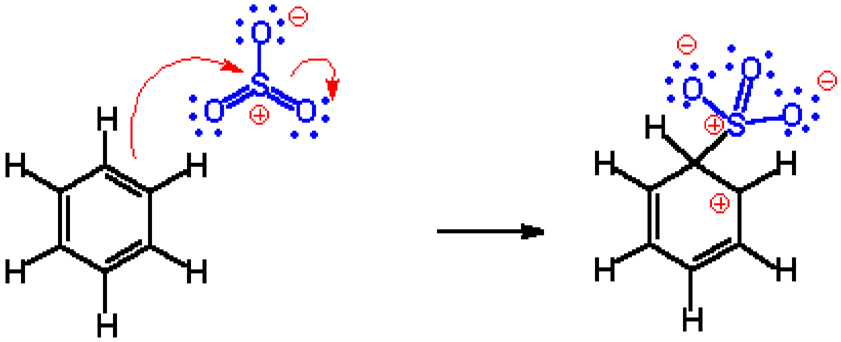
- **Formation of the electrophile**

  The mixture of SO_3 in sulfuric acid contains several reactive species. SO_3 is a good electrophile because of the partial positive charge on the sulfur atom.

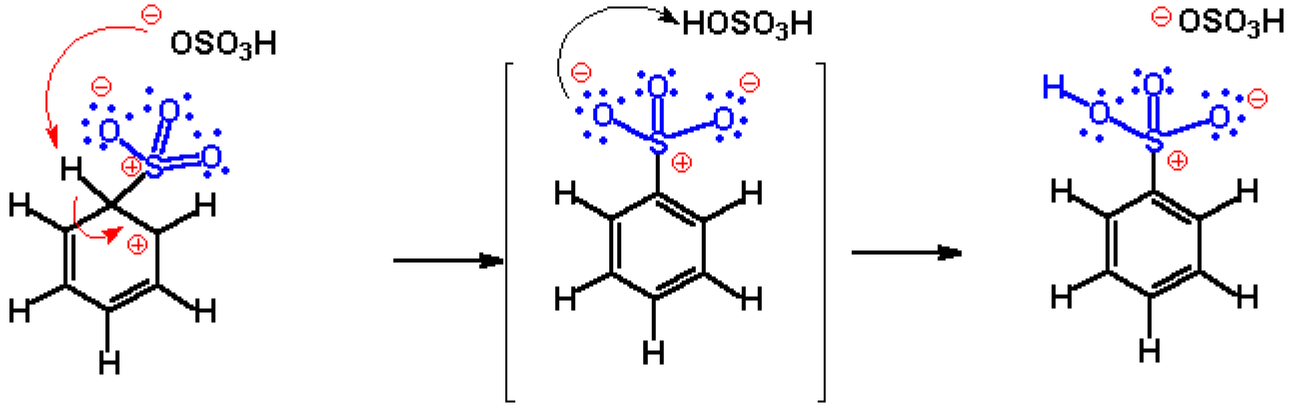


- **Addition of the electrophile to the benzene ring**

  The electrophile adds to form the cyclohexadienyl carbocation destroying the aromaticity.



- **Elimination of H^+ to restore the aromatic ring**



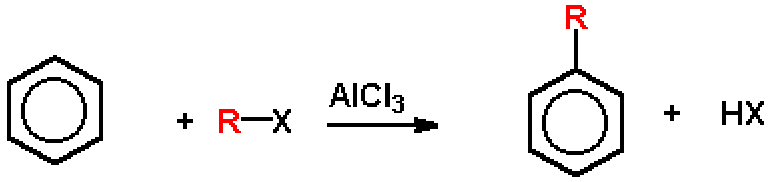
Applications

Because the sulfonation reaction is reversible it may be used to block a position on an aromatic ring then be removed.

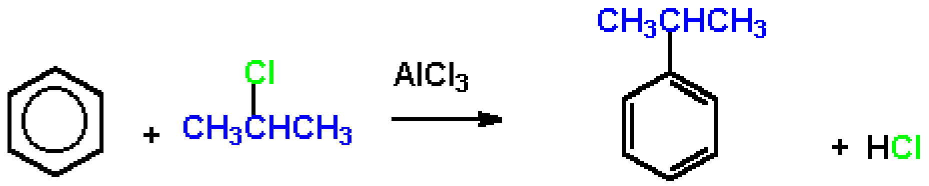
Sulfonic acid groups are polar and make the nonpolar aromatic water soluble. Many dyes, detergents, and drugs contain sulfonic acid groups.

Friedel-Crafts Alkylation

An important electrophilic aromatic substitution reaction is the Friedel-Crafts alkylation which forms alkyl benzenes. This reaction was discovered in 1877 by Charles Friedel, a French chemist, and James Mason Craft, an American. In this reaction an alkyl halide reacts with an aromatic compound in the presence of a Lewis Acid catalyst, often $AlCl_3$.



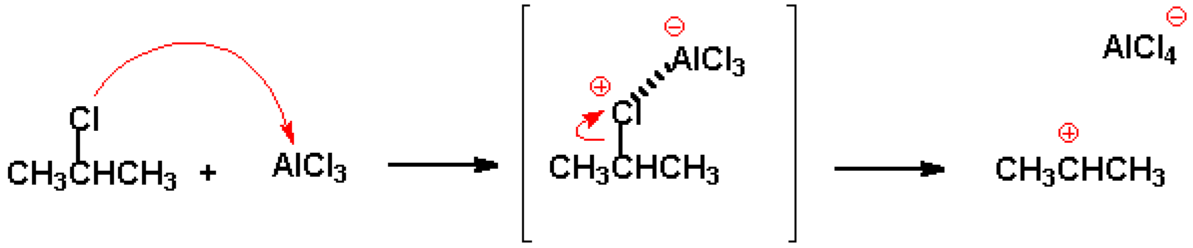
For example, benzene reacts with 2-chloropropane in the presence of aluminum trichloride to form 2-phenylpropane.



Mechanism

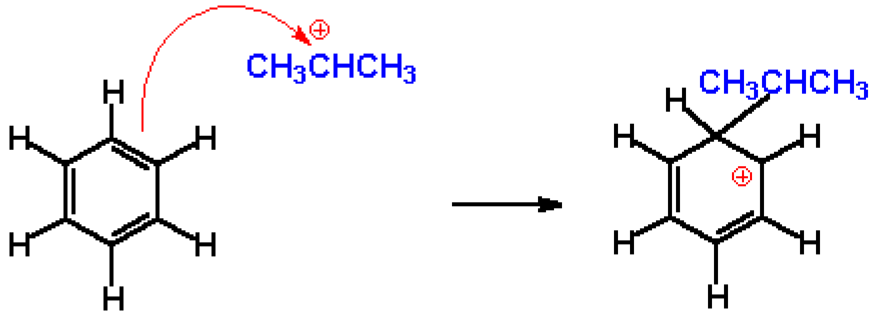
- **Formation of the electrophile**

With tertiary and secondary halides, the electrophile is probably the carbocation. For primary halides, the carbocation is very unstable, and the electrophile is probably a complex with the Lewis acid catalyst.

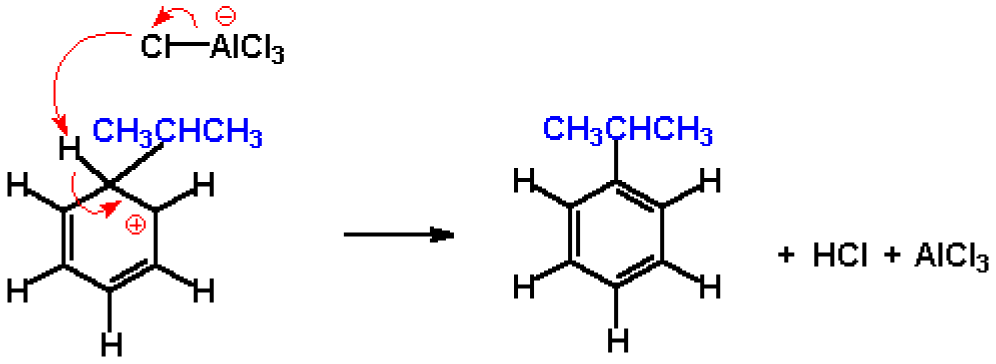


- **Addition of the electrophile to the benzene ring**

The electrophile adds to form the cyclohexadienyl carbocation destroying the aromaticity.

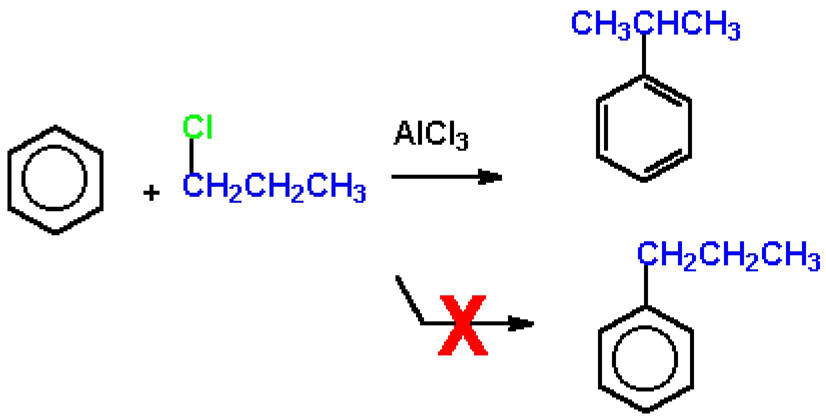


- **Elimination of H^+ to restore the aromatic ring**

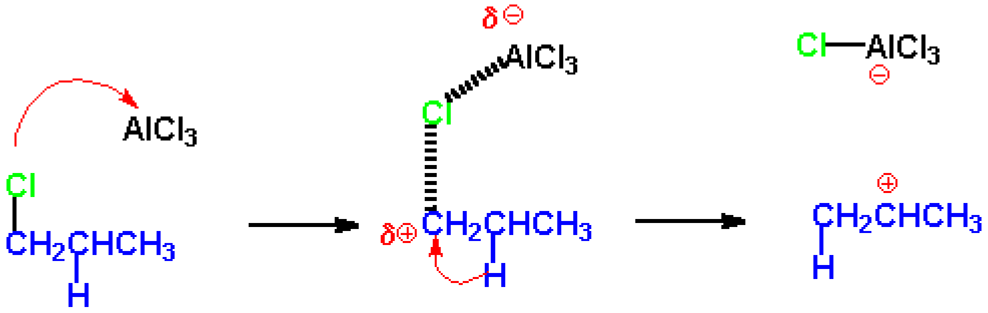


Limitation

With primary halides, the electrophile is a 1^{o} carbocation which usually undergoes rearrangement to give a more stable 2^{o} or 3^{o} carbocation. For example, the reaction of 1-chloropropane with benzene gives 2-phenylpropane as the major product not 1-phenylpropane.

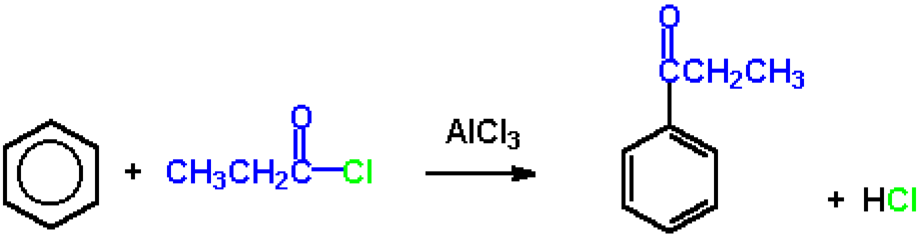


Rearrangement of intermediate electrophile occurs by a shift of a hydrogen atom.



Friedel-Crafts Acylation

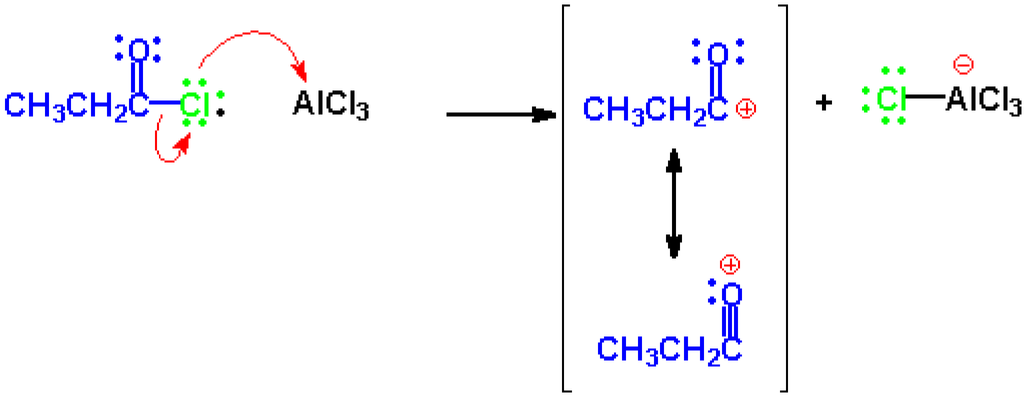
The Friedel-Crafts acylation reaction is similar to the alkylation reaction except that the electrophile is formed from an acid halide (acyl halide) instead of an alkyl halide.



Mechanism

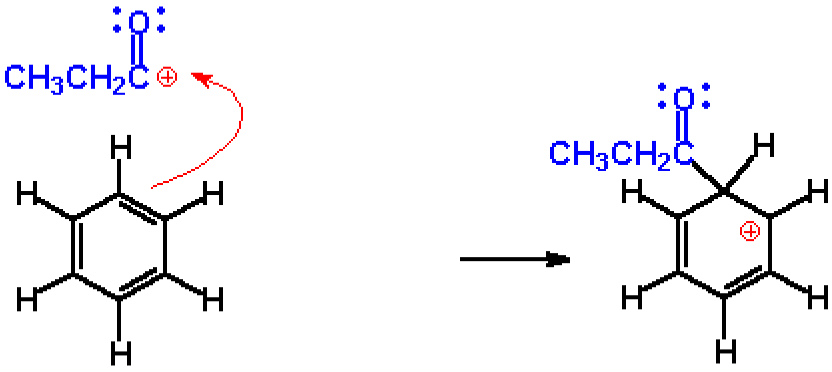
- **Formation of the electrophile**

  The electrophile is an acyl cation (usually called an acylium ion). This acylium ion is relative stable.

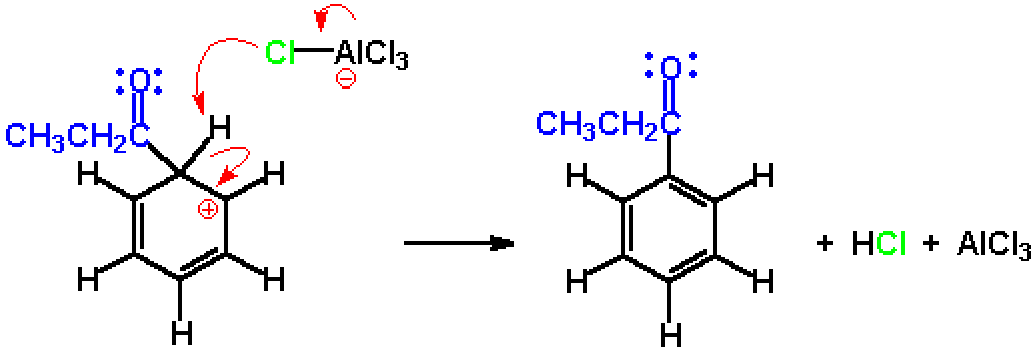


- **Addition of the electrophile to the benzene ring**

The electrophile adds to form the cyclohexadienyl carbocation destroying the aromaticity.



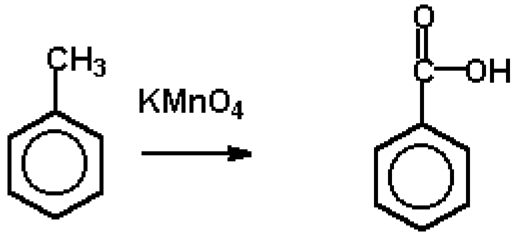
- **Elimination of H^+ to restore the aromatic ring**



next(Oxidation of alkyl benzenes)

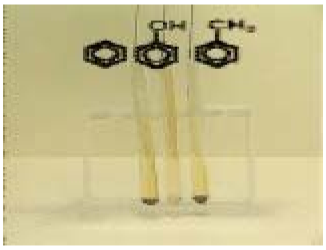
Oxidation of Alkyl Benzenes

The benzene ring is usually stable to oxidizing reagents; however, alkyl sidechains can be oxidized with potassium permanganate to give benzoic acids.



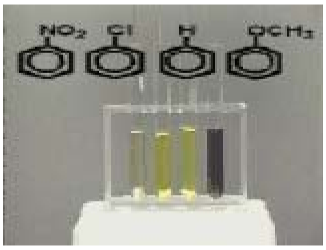
Reactivity and Orientation in Electrophilic Aromatic Substitution

Let's compare the reactivity of bromine with benzene, phenol, and toluene.



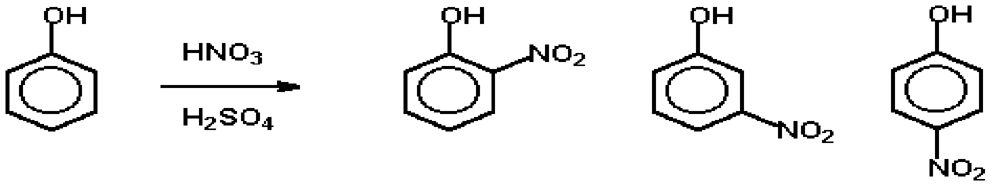
In the absence of a catalyst benzene and toluene do not react with bromine but phenol reacts immediately.

Substituents affect the electron density and reactivity of the benzene ring toward electrophilic addition. Compare the electron densities of the following aromatic compounds.



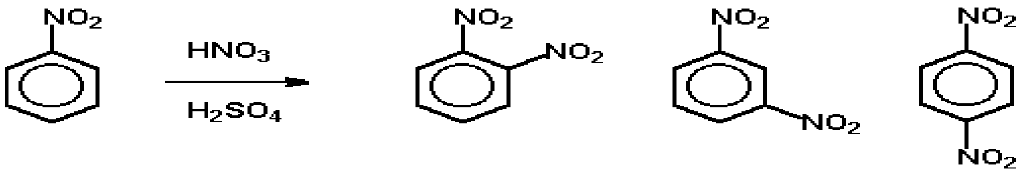
Anisole (methoxybenzene) is highly reactive toward electrophiles while nitrobenzene is much less reactive than benzene and is sometimes used as a solvent for electrophilic aromatic substitution reactions.We can arrange substituted benzenes according to their reactivity toward electrophiles. Substitutents that render the aromatic ring more reactive toward electrophiles than benzene are activators. Substituents that render the aromatic ring less reactive toward electrophiles than benzene are deactivators.

In addition to differences in reactivity, substituted benzenes display differences in the orientation of their substituents. Nitration of phenol gives a mixture of three nitrophenols with the major isomers having the nitro group at the ortho and para position. Only a trace of m-nitophenol is produced. If nitration of phenol occurred randomly at the 5 available sites, we would predict 40% ortho (2/5 positions), 20% para (1/5 positions), and 40% meta (2/5 positions). The discrepancy of experiment with prediction reveals that the hydroxyl group of phenol is orienting the electrophile at the ortho and para positions. Substituents like hydroxyl are called ortho, para directors.



experimental yield	~50%	trace	~50%
predicted yield	40%	40%	20%

Nitration of nitrobenzene occurs much slower than nitration of benzene since the nitro group is a deactivator. The nitro group also dramatically affects the orientation of the substitution by giving almost exclusively the meta product. Substituent like the nitro group are called meta directors.

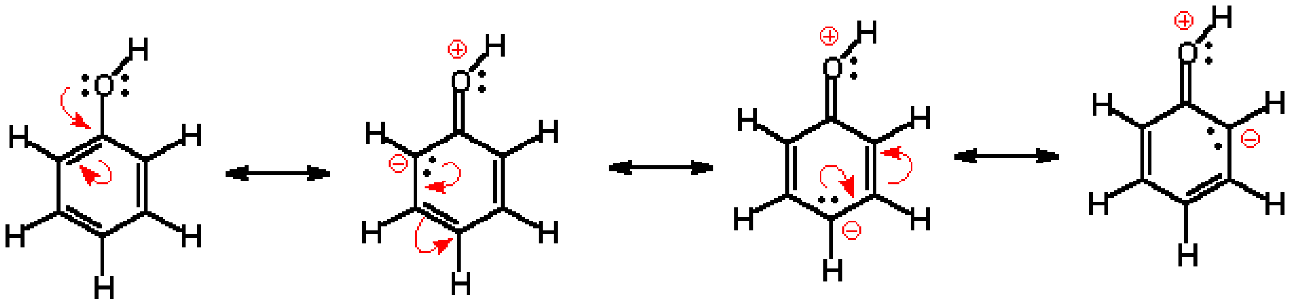


experimental yield	trace	~ 93%	trace
predicted yield	40%	40%	20%

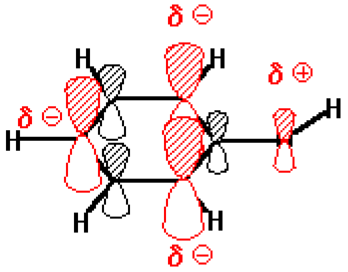
Examination of Reactivity

All of the mechanisms we have seen for electrophilic aromatic substitution involve attack by an electrophile on an aromatic ring. It is reasonable to assume that activating groups increase the electron density of the aromatic ring and deactivating groups decrease the electron density of the aromatic ring relative to benzene.

Consider the activating hydroxyl group of phenol. Oxygen is more electronegative than carbon and should withdraw electrons from the aromatic ring through the sigma bond (inductive effect). However, the presence of nonbonded 2p electron pairs on the oxygen allow donation of electrons to the aromatic ring (resonance effect). For oxygen resonance effects are more important than inductive effects and the net effect is an increase in electron density on the ring. With chlorine and bromine, the nonbonded electrons are in higher orbitals (3p and 4p) and give poor resonance overlap. The strong electronegative effects of these atoms dominate making them deactivators. The electron density remains higher in the ortho and para positions and the halogens are ortho, para directors.

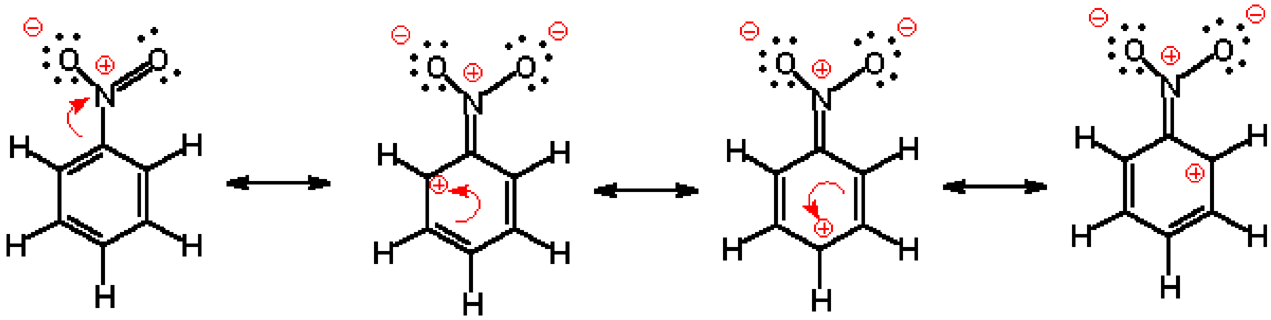


Resonance structures of phenol showing how the electron density is increased at the ortho and para positions.

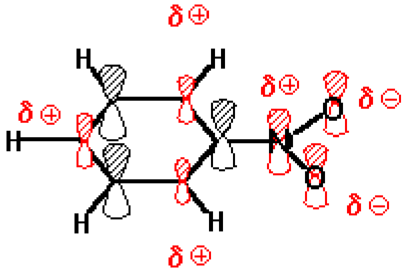


Molecular orbital representation of phenol showing how the electron density is increased at the ortho and para positions.

The nitro group is a deactivator and a meta director. Deactivators withdraw electron density from the aromatic ring and decrease its reactivity. Again, both inductive and resonance effects are factors. For the nitrogroup, resonance effects are the major factor and show that the nitro group is electron withdrawing and it withdraws electrons from the ortho and para positions. The meta positions have the higher electron density and are the site of attack by the electrophile.



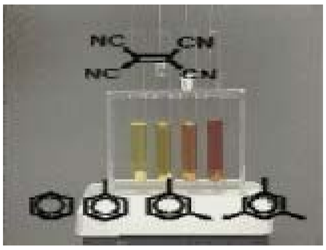
Resonance structures of nitrobenzene showing how the electron density is decreased at the ortho and para positions.



Molecular orbital representation of nitrobenzene showing how the electron density is decreased at the ortho and para positions.

Effect of Several Substituents on Reactivity toward Electrophilic Substitution

What happens to the aromatic ring if several substituents are present. Let's compare the electron density of benzene with mono-, di-, and trimethyl benzenes.



If several substituents are located on a benzene, each substituent exerts an additive effect. Each electron donating methyl group adds electron density to the ring. This increase of electron density is reflected in the reactivity of the the various methyl benzenes toward chlorine.

Conversely, with deactivating groups, each group further decreases the electron density of the benzene ring and lowers the reactivity toward electrophilic substitution.

Summary of Substituent Effects

The following table lists common aromatic substituents according to their effect on reactivity and orientation in electrophilic substitution reactions. Note that ortho, para directors may be activating or deactivating but all meta directors are deactivating groups.

Ortho, Para Directors		Meta Directors
Activating Groups	Deactivating Groups	Deactivating Groups
strongly activating • $-NH_2$ • -OH	• F • Cl • Br • I	• $-NO_2$ • -CN • $-CO_2H$ • $-SO_3H$ • -C=O
moderately activating • $-OCH_3$ • $-NHCOCH_3$		
weakly activating • $-C_6H_5$ • alkyl		