Objectives

After completing this section, you should be able to

1. write a balanced equation for the halogenation (F, Cl, Br, I) of benzene in the presence of a suitable catalyst or promoter.
2. draw the resonance contributors for the carbocation which is formed during the reaction of chlorine or bromine with benzene.
3. write the equation for the nitration and sulfonation of benzene.
4. write the detailed mechanism for the nitration and sulfonation of benzene.
5. write the equation for the reduction of an aromatic nitro compound to an amine.
6. identify aromatic sulfonation as being a reversible process, and describe the conditions under which the forward and reverse reactions are favoured.
7. write the equation for the desulfonation of an aromatic sulfonic acid.
8. identify aromatic sulfonic acids as being key intermediates in the manufacture of sulfa drugs.

Key Terms

Make certain that you can define, and use in context, the key term below.

• nitronium ion, (NO\(^{+2}\))

Study Notes

You should be careful to remember that iodine and fluorine cannot be introduced into an aromatic ring by the method used for bromine and chlorine. On its own, iodine is unreactive with aromatic rings, but one method for aromatic iodination is treatment in the presence of a copper salt such as copper(II)chloride where I\(^2\) is oxidized to the more electrophilic species I\(^+\).

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synthesis of iodosobenzene from benzene
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In contrast, fluorine is too reactive, so it cannot be used directly for aromatic fluorination. However, fluorinating agents like 1-(chloromethyl)-4-fluoro-1,4-diazoniabicyclo[2.2.2]octane ditetrafluoroborate (also known as F-TEDA-BF\(_4\)) sold commercially as Sectfluor® offer convenient sources of “F\(^+\)” for this type of reaction.

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fluorinating agent F-TEDA-BF4
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F-TEDA-BF4
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synthesis of fluorobenzene from benzene
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The overall equation for the formation of nitronium ions by the action of sulfuric acid on nitric acid is

\[
\text{HNO}_3 + 2\text{H}_2\text{SO}_4 \leftrightarrow \text{H}_3\text{O}^+ + \text{NO}_2^+ + \text{HSO}_4^- \]

\]}$
The ability of compounds such as nitronium tetrafluoroborate to bring about the nitration of aromatic compounds is good evidence in support of the proposed mechanism.

The nitration of an aromatic ring is an important synthetic pathway to generating arylamines. The reaction below shows one common method of reducing the nitro group. (Amines are examined in more detail in Chapter 24.)

reduction of nitrobenzene to aniline

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**Halogenation of Benzene**

Halogenation is an example of electrophillic aromatic substitution. In electrophilic aromatic substitutions, a benzene is attacked by an electrophile which results in substitution of hydrogens. However, halogens are not electrophillic enough to break the aromaticity of benzenes, which require a catalyst to activate.

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**Activation of Halogen**

(where X= Br or Cl, we will discuss further in detail later why other members of the halogen family Flourine and Iodine are not used in halogenation of benzenes)

![Reaction Diagram](image)

Hence, Halogen needs the help and aid of Lewis Acidic Catalysts to activate it to become a very strong electrophile. Examples of these activated halogens are Ferric Hallides (FeX$_3$) Aluminum Halides (AlX$_3$) where X= Br or Cl. In the following examples, the halogen we will look at is Bromine.

In the example of bromine, in order to make bromine electrophillic enough to react with benzene, we use the aid of an aluminum halide such as aluminum bromide.
With aluminum bromide as a Lewis acid, we can mix Br₂ with AlBr₃ to give us Br⁺. The presence of Br⁺ is a much better electrophile than Br₂ alone. Bromination is achieved with the help of AlBr₃ (Lewis acid catalysts) as it polarizes the Br-Br bond. The polarization causes the bromine atoms within the Br-Br bond to become more electrophilic. The presence of Br⁺ compared to Br₂ alone is a much better electrophile that can then react with benzene.

As the bromine has now become more electrophilic after activation of a catalyst, an electrophillic attack by the benzene occurs at the terminal bromine of Br-Br-AlBr₃. This allows the other bromine atom to leave with the AlBr₃ as a good leaving group, AlBr₄⁻.

After the electrophillic attack of bromide to the benzene, the hydrogen on the same carbon as bromine substitutes the carbocation in which resulted from the attack. Hence it being an electrophilic aromatic SUBSTITUTION. Since the by-product aluminum tetrabromide is a strong nucleophile, it pulls of a proton from the Hydrogen on the same carbon as bromine.
In the end, AlBr₃ was not consumed by the reaction and is regenerated. It serves as our catalyst in the halogenation of benzenes.

Dissociation Energies of Halogens and its Effect on Halogenation of Benzenes

The electrophillic bromination of benzenes is an exothermic reaction. Considering the exothermic rates of aromatic halogenation decreasing down the periodic table in the Halogen family, Flourination is the most exothermic and Iodination would be the least. Being so exothermic, a reaction of flourine with benzene is explosive! For iodine, electrophillic iodination is generally endothermic, hence a reaction is often not possible. Similar to bromide, chlorination would require the aid of an activating presence such as Alumnium Chloride or Ferric Chloride. The mechanism of this reaction is the same as with Bromination of benzene.

Nitration and sulfonation of benzene are two examples of electrophilic aromatic substitution. The nitronium ion (NO₂⁺) and sulfur trioxide (SO₃) are the electrophiles and individually react with benzene to give nitrobenzene and benzenesulfonic acid respectively.

Nitration of Benzene

The source of the nitronium ion is through the protonation of nitric acid by sulfuric acid, which causes the loss of a water molecule and formation of a nitronium ion.

Sulfuric Acid Activation of Nitric Acid

The first step in the nitration of benzene is to activate HNO₃ with sulfuric acid to produce a stronger electrophile, the nitronium ion.
Because the nitronium ion is a good electrophile, it is attacked by benzene to produce Nitrobenzene.

**Mechanism**

(Resonance forms of the intermediate can be seen in the generalized electrophilic aromatic substitution)

**Sulfonation of Benzene**

Sulfonation is a reversible reaction that produces benzenesulfonic acid by adding sulfur trioxide and fuming sulfuric acid. The reaction is reversed by adding hot aqueous acid to benzenesulfonic acid to produce benzene.

**Mechanism**

To produce benzenesulfonic acid from benzene, fuming sulfuric acid and sulfur trioxide are added. Fuming sulfuric acid, also referred to as *oleum*, is a concentrated solution of dissolved sulfur trioxide in sulfuric acid. The sulfur in sulfur trioxide is electrophilic because the oxygens pull electrons away from it because oxygen is very electronegative. The benzene attacks the sulfur (and subsequent proton transfers occur) to produce benzenesulfonic acid.
Reverse Sulfonation

Sulfonation of benzene is a reversible reaction. Sulfur trioxide readily reacts with water to produce sulfuric acid and heat. Therefore, by adding heat to benzenesulfonic acid in diluted aqueous sulfuric acid the reaction is reversed.

Further Applications of Nitration and Sulfonation

Nitration is used to add nitrogen to a benzene ring, which can be used further in substitution reactions. The nitro group acts as a ring deactivator. Having nitrogen present in a ring is very useful because it can be used as a directing group as well as a masked amino group. The products of aromatic nitration are very important intermediates in industrial chemistry.

Because sulfonation is a reversible reaction, it can also be used in further substitution reactions in the form of a directing blocking group because it can be easily removed. The sulfonic group blocks the carbon from being attacked by other substituents and after the reaction is completed it can be removed by reverse sulfonation. Benzenesulfonic acids are also used in the synthesis of detergents, dyes, and sulfa drugs. Bezenesulfonyl Chloride is a precursor to sulfonamides, which are used in chemotherapy.

Outside Links

Aromatic Halogenation

- [http://www.chemguide.co.uk/mechanism...ogenation.html](http://www.chemguide.co.uk/mechanism...ogenation.html)

Aromatic Sulfonation

- Video: [http://www.youtube.com/watch?v=s1qJ1...eature=related](http://www.youtube.com/watch?v=s1qJ1...eature=related)
Aromatic Nitration

- Video: [http://www.youtube.com/watch?v=i7ucl...eature=related](http://www.youtube.com/watch?v=i7ucl...eature=related)
- Interactive 3D Reaction: [http://www.chemtube3d.com/Electrophi...20benzene.html](http://www.chemtube3d.com/Electrophi...20benzene.html)

Problems

1. What is/are the required reagent(s) for the following reaction:

![SO_3H](image)

2. What is the product of the following reaction:

![SO_3H](image) → ![H_2O](image) → ![H_2SO_4](image)

3. Why is it important that the nitration of benzene by nitric acid occurs in sulfuric acid?

4. Write a detailed mechanism for the sulfonation of benzene, including all resonance forms.

5. Draw an energy diagram for the nitration of benzene. Draw the intermediates, starting materials, and products. Label the transition states. (For questions 1 and 2 see Electrophilic Aromatic Substitution for hints)

For other problems involving Electrophilic Aromatic Substitution and similar reactions see:

- Electrophilic Aromatic Substitution
- Activating and Deactivating Benzene Rings
- Electrophilic Attack on Disubstituted Benzenes

Solutions

1. SO_3 and H_2SO_4 (fuming)
3. Sulfuric acid is needed in order for a good electrophile to form. Sulfuric acid protonates nitric acid to form the nitronium ion (water molecule is lost). The nitronium ion is a very good electrophile and is open to attack by benzene. Without sulfuric acid the reaction would not occur.

References


Questions

Q16.2.1
In each case, how many products would be expected for the bromination of \( p \)-xylene, \( o \)-xylene, and \( m \)-xylene?

Q16.2.2
If toluene is treated with \( \text{D}_2\text{SO}_4 \) all the hydrogen’s are replaced with deuterium. Explain. (might need to draw mechanism)

Solutions

S16.2.1

The deuterium is added to the ring. When the ring “re-aromatizes” the base scavenges the hydrogen before the deuterium and therefore is left on the ring. Continues for the rest of the hydrogen on the ring.
Contributors and Attributions

- Dr. Dietmar Kennepohl FCIC (Professor of Chemistry, Athabasca University)
- Prof. Steven Farmer (Sonoma State University)
- Catherine Nguyen