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Carbon and its Compounds

Carbon's Capacity to Share Electrons:

Carbon has four electrons in its outermost shell and needs to gain or lose four electrons to attain noble gas configuration. If it were to gain or lose electrons –

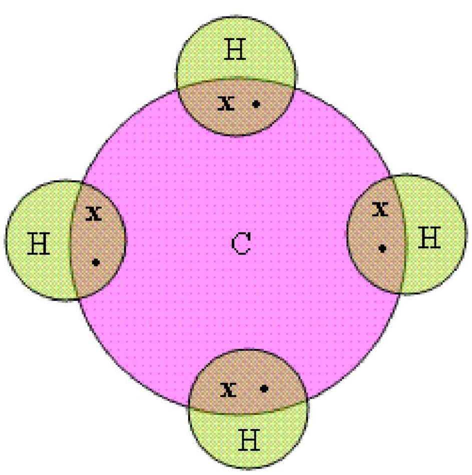
(i) It could gain four electrons forming C^{4-} anion. But it would be difficult for the nucleus with six protons to hold on to ten electrons, that is, four extra electrons.

(ii) It could lose four electrons forming C^{4+} cation. But it would require a large amount of energy to remove four electrons leaving behind a carbon cation with six protons in its nucleus holding on to just two electrons.

Carbon overcomes this problem by sharing its valence electrons with other atoms of carbon or with atoms of other elements. Not just carbon, but many other elements form molecules by sharing electrons in this manner. The shared electrons 'belong' to the outer shells of both the atoms and lead to both atoms attaining the noble gas configuration.

This type of bond formed by sharing of electrons is called covalent bond. Covalently bonded molecules are seen to have strong bonds within the molecule, but intermolecular forces are small. This gives rise to the low melting and boiling points of these compounds. Since the electrons are shared between atoms and no charged particles are formed, such covalent compounds are generally poor conductors of electricity.

Let us now take a look at methane, which is a compound of carbon. Methane is widely used as a fuel and is a major component of bio-gas and Compressed Natural Gas (CNG). It is also one of the simplest compounds formed by carbon. Methane has a formula CH_4. Hydrogen, as you know, has a valency of 1. Carbon is tetravalent because it has four valence electrons. In order to achieve noble gas configuration, carbon shares these electrons with four atoms of hydrogen as shown below:



Allotropes of carbon: The element carbon occurs in different forms in nature with widely varying physical properties. Both diamond and graphite are formed by carbon atoms, the difference lies in the manner in which the carbon atoms are bonded to one another. In diamond, each carbon atom is bonded to four other carbon atoms forming a rigid three-dimensional structure. In graphite, each

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carbon atom is bonded to three other carbon atoms in the same plane giving a hexagonal array. One of these bonds is a double-bond, and thus the valency of carbon is satisfied. Graphite structure is formed by the hexagonal arrays being placed in layers one above the other.

VERSATILE NATURE OF CARBON

The numbers of carbon compounds whose formulae are known to chemists was recently estimated to be about three million! This outnumbers by a large margin the compounds formed by all the other elements put together. The nature of the covalent bond enables carbon to form a large number of compounds. Two factors noticed in the case of carbon are –

(i) Carbon has the unique ability to form bonds with other atoms of carbon, giving rise to large molecules. This property is called catenation. These compounds may have long chains of carbon, branched chains of carbon or even carbon atoms arranged in rings. In addition, carbon atoms may be linked by single, double or triple bonds. Compounds of carbon, which are linked by only single bonds between the carbon atoms are called saturated compounds. Compounds of carbon having double or triple bonds between their carbon atoms are called unsaturated compounds. No other element exhibits the property of catenation to the extent seen in carbon compounds. Silicon forms compounds with hydrogen which have chains of upto seven or eight atoms, but these compounds are very reactive. The carbon-carbon bond is very strong and hence stable. This gives us the large number of compounds with many carbon atoms linked to each other.

(ii) Since carbon has a valency of four, it is capable of bonding with four other atoms of carbon or atoms of some other mono-valent element. Compounds of carbon are formed with oxygen, hydrogen, nitrogen, sulphur, chlorine and many other elements giving rise to compounds with specific properties which depend on the elements other than carbon present in the molecule.

Again the bonds that carbon forms with most other elements are very strong making these compounds exceptionally stable. One reason for the formation of strong bonds by carbon is its small size. This enables the nucleus to hold on to the shared pairs of electrons strongly. The bonds formed by elements having larger atoms are much weaker.

Organic compounds

The two characteristic features seen in carbon, that is, tetravalency and catenation, put together give rise to a large number of compounds. Many have the same non-carbon atom or group of atoms attached to different carbon chains. These compounds were initially extracted from natural substances and it was thought that these carbon compounds or organic compounds could only be formed within a living system. That is, it was postulated that a ‘vital force’ was necessary for their synthesis. Friedrich Wöhler disproved this in 1828 by preparing urea from ammonium cyanate. But carbon compounds, except for oxides of carbon, carbonate and hydrogencarbonate salts continue to be studied under organic chemistry.

Saturated and Unsaturated Carbon Compounds

In order to arrive at the structure of simple carbon compounds, the first step is to link the carbon atoms together with a single bond and then use the hydrogen atoms to satisfy the remaining valencies of carbon. For example, the structure of ethane is arrived in the following steps –

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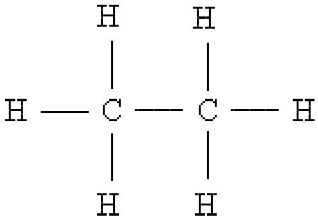
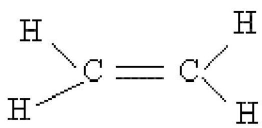
Step I



Step II

C_2H_6 Ethane



Step II

C_2H_4 Ethene

• In the first example of ethane all valency of carbon atoms is satisfied, hence this is called as saturated carbon compound or saturated organic compound.

• In the second example of ethane valency of carbon atom is not fully satisfied, hence this is called as unsaturated organic compound.

• Compounds formed by carbon and hydrogen only are called hydrocarbons.

• Those hydrocarbons which have single bonds in molecular structure are called alkanes. Generic formula for alkanes is $C_nH_{(2n+2)}$

• Hydrocarbons with double bonds are called alkenes. Generic formula for alkenes is C_nH_{2n}

• Hydrocarbons with triple bonds are called alkynes. Generic formula for alkynes is C_nH_n

Carbon seems to be a very friendly element. So far we have been looking at compounds of carbon and hydrogen. But carbon also forms bonds with other elements such as halogens, oxygen, nitrogen and sulphur. In a hydrocarbon chain, one or more hydrogens can be replaced by these elements, such that the valency of carbon remains satisfied. In such compounds, the element replacing hydrogen is referred to as a heteroatom. These heteroatoms confer specific properties to the compound, regardless of the length and nature of the carbon chain and hence are called functional groups. The functional group is attached to the carbon chain through this valency by replacing one hydrogen atom or atoms.

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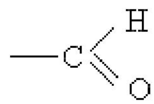
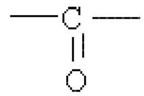
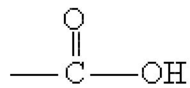
Heteroatom	Functional Group	Formula of Functional Group
Cl/Br	Halo – (Chloro/bromo)	-Cl, -Br (Substitute for hydrogen atom)
Oxygen	1. Alcohol 2. Aldehyde 3. Ketone 4. Carboxylic acid	—OH   

Homologous Series

The presence of a functional group such as alcohol dictates the properties of the carbon compound, regardless of the length of the carbon chain. For example, the chemical properties of CH_3OH, C_2H_5OH, C_3H_7OH and C_4H_9OH are all very similar. Hence, such a series of compounds in which the same functional group substitutes for hydrogen in a carbon chain is called a homologous series.

As the molecular mass increases in any homologous series, a gradation in physical properties is seen. This is because the melting points and boiling points increase with increasing molecular mass. Other physical properties such as solubility in a particular solvent also show a similar gradation. But the chemical properties, which are determined solely by the functional group, remain similar in a homologous series.

Nomenclature of Carbon Compounds

The names of compounds in a homologous series are based on the name of the basic carbon chain modified by a “prefix” “phrase before” or “suffix” “phrase after” indicating the nature of the functional group.

Naming a carbon compound can be done by the following method –

(i) Identify the number of carbon atoms in the compound. A compound having three carbon atoms would have the name propane.

(ii) In case a functional group is present, it is indicated in the name of the compound with either a prefix or a suffix.

(iii) If the name of the functional group is to be given as a suffix, the name of the carbon chain is modified by deleting the final ‘e’ and adding the appropriate suffix.

For example, a three-carbon chain with a ketone group would be named in the following manner – Propane – ‘e’ = propan + ‘one’ = propanone.

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(iv) If the carbon chain is unsaturated, then the final 'ane' in the name of the carbon chain is substituted by 'ene' or 'yne'. For example, a three-carbon chain with a double bond would be called propene and if it has a triple bond, it would be called propyne.

Functional Group	Prefix/ Suffix	Example
Halogen	Prefix – chloro	Chloropropane, Bromopropane
Alcohol	Suffix – ol	Propanol
Aldehyde	Suffix – al	Propanal
Ketone	Suffix – one	Propanone
Carboxyllic acid	Suffix – oic acid	Propanoic acid
Double bond (alkenes)	Suffiex – ene	Propene
Triple bond (alkynes)	Suffix – yne	Propyne

CHEMICAL PROPERTIES OF CARBON COMPOUNDS

Combustion: Carbon, in all its allotropic forms, burns in oxygen to give carbon dioxide along with the release of heat and light. Most carbon compounds also release a large amount of heat and light on burning.

Saturated hydrocarbons will generally give a clean flame while unsaturated carbon compounds will give a yellow flame with lots of black smoke. However, limiting the supply of air results in incomplete combustion of even saturated hydrocarbons, giving a sooty flame. The gas/kerosene stove used at home has inlets for air so that a sufficiently oxygen-rich mixture is burnt to give a clean blue flame. If you observe the bottoms of cooking vessels getting blackened, it means that the air holes are blocked and fuel is getting wasted. Fuels such as coal and petroleum have some amount of nitrogen and sulphur in them. Their combustion results in the formation of oxides of sulphur and nitrogen which are major pollutants in the environment.

Oxidation: Carbon compounds can be easily oxidised on combustion. In addition to this complete oxidation, we have reactions in which alcohols are converted to carboxylic acids –

$$CH_3-CH_2OH \xrightarrow[\text{Or Acidified } K_2Cr_2O_7 + \text{Heat}]{\text{Alkaline } KMnO_4 + \text{Heat}} CH_3COOH$$

Addition Reaction: Unsaturated hydrocarbons add hydrogen in the presence of catalysts such as palladium or nickel to give saturated hydrocarbons. Catalysts are substances that cause a reaction to occur or proceed at a different rate without the reaction itself being affected. This reaction is commonly used in the hydrogenation of vegetable oils using a nickel catalyst.

Substitution Reaction: Saturated hydrocarbons are fairly unreactive and are inert in the presence of most reagents. However, in the presence of sunlight, chlorine is added to hydrocarbons in a very fast reaction. Chlorine can replace the hydrogen atoms one by one. It is called a substitution reaction because one type of atom or a group of atoms takes the place of another. A number of products are usually formed with the higher homologues of alkanes.

SOME IMPORTANT CARBON COMPOUNDS – ETHANOL AND ETHANOIC ACID

Properties of Ethanol: Ethanol is a liquid at room temperature. Ethanol is commonly called alcohol and is the active ingredient of all alcoholic drinks. In addition, because it is a good solvent, it is also

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used in medicines such as tincture iodine, cough syrups, and many tonics. Ethanol is also soluble in water in all proportions. Consumption of small quantities of dilute ethanol causes drunkenness. Even though this practice is condemned, it is a socially widespread practice. However, intake of even a small quantity of pure ethanol (called absolute alcohol) can be lethal. Also, long-term consumption of alcohol leads to many health problems.

Reactions of Ethanol

(i) Reaction with sodium – Alcohols react with sodium leading to the evolution of hydrogen. With ethanol, the other product is sodium ethoxide.

$$2Na + 2CH_3 - CH_2OH \longrightarrow \underset{\text{Sodium ethoxide}}{2CH_3CH_2O^-Na^+} + H_2$$

(ii) Reaction to give unsaturated hydrocarbon: Heating ethanol at 443 K with excess concentrated sulphuric acid results in the dehydration of ethanol to give ethene – The concentrated sulphuric acid can be regarded as a dehydrating agent which removes water from ethanol.

$$CH_3 - CH_2OH \xrightarrow{\text{Hot conc } H_2SO_4} CH_2 = CH_2 + H_2O$$

Effects of Alcohol: When large quantities of ethanol are consumed, it tends to slow metabolic processes and to depress the central nervous system. This results in lack of coordination, mental confusion, drowsiness, lowering of the normal inhibitions, and finally stupour. The individual may feel relaxed but does not realise that his sense of judgement, sense of timing, and muscular coordination have been seriously impaired. Unlike ethanol, intake of methanol in very small quantities can cause death. Methanol is oxidised to methanal in the liver. Methanal reacts rapidly with the components of cells. It causes the protoplasm to get coagulated, in much the same way an egg is coagulated by cooking. Methanol also affects the optic nerve, causing blindness. Ethanol is an important industrial solvent. To prevent the misuse of ethanol produced for industrial use, it is made unfit for drinking by adding poisonous substances like methanol to it. Dyes are also added to colour the alcohol blue so that it can be identified easily. This is called denatured alcohol.

Properties of Ethanoic Acid:

Ethanoic acid is commonly called acetic acid and belongs to a group of acids called carboxylic acids. 5-8% solution of acetic acid in water is called vinegar and is used widely as a preservative in pickles. The melting point of pure ethanoic acid is 290 K and hence it often freezes during winter in cold climates. This gave rise to its name glacial acetic acid. The group of organic compounds called carboxylic acids are obviously characterised by a special acidity. However, unlike mineral acids like HCl, which are completely ionised, carboxylic acids are weak acids.

Reactions of ethanoic acid:

(i) Esterification reaction: Esters are most commonly formed by reaction of an acid and an alcohol. Ethanoic acid reacts with absolute ethanol in the presence of an acid catalyst to give an ester –

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$$CH_3-CHOOH + CH_3-CH_2OH \xrightarrow{Acid} CH_2-\underset{\underset{O}{||}}{C}-O-CH_2-CH_3$$

Ethanoic acid Ethanol Ester

Esters are sweet-smelling substances. These are used in making perfumes and as flavouring agents. Esters react in the presence of an acid or a base to give back the alcohol and carboxylic acid. This reaction is known as saponification because it is used in the preparation of soap.

Alcohol as a fuel: Sugarcane plants are one of the most efficient convertors of sunlight into chemical energy. Sugarcane juice can be used to prepare molasses which is fermented to give alcohol (ethanol). Some countries now use alcohol as an additive in petrol since it is a cleaner fuel which gives rise to only carbon dioxide and water on burning in sufficient air (oxygen).

(ii) Reaction with a base: Like mineral acids, ethanoic acid reacts with a base such as sodium hydroxide to give a salt (sodium ethanoate or commonly called sodium acetate) and water:

$$NaOH + CH_3COOH \longrightarrow CH_3COONa + H_2O$$

(iii) Reaction with carbonates and hydrogencarbonates: Ethanoic acid reacts with carbonates and hydrogencarbonates to give rise to a salt, carbon dioxide and water. The salt produced is commonly called sodium acetate.

$$NaOH + CH_3COOH \longrightarrow CH_3COONa + H_2O$$