

STEREOCHEMISTRY OF MOLECULES WITHOUT A CHIRAL CENTRE

Structure

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4.1 INTRODUCTION

In the first two units of this course you have learnt the stereochemistry of the molecules with one, two, three or more chiral centres. There we discussed the concept of chirality as one of the conditions for the molecules to show optical activity. You have learned the concept of racemisation and resolution of enantiomers after going through those units. In the third unit you read about conformational isomerism. You learnt to draw the conformational isomers of cyclohexane and related compounds and explain their stability. So far we have considered molecules that have chiral centres and therefore exhibited the optical activity.

In the present unit we would discuss the molecules that do not have chiral centres but still show optical isomerism due to the presence of a chiral axis or a plane as the factors responsible for the optical activity. These are included in the category of complex systems. We will discuss the axial chirality, planar chirality and helicity in molecules. The allenes, spiranes, alkylidenes, ansa compounds, cyclophanes, catenanes, adamantanes, etc. belong to the group of such compounds. We would start with allenes in the following section.

Expected Learning Outcomes

After studying this unit you should be able to:

- ❖ explain the concept of stereoisomerism in molecules without chiral centres;
- ❖ define and elaborate the axial, planar and helical chirality;
- ❖ describe the stereochemistry of allenes, spiranes and Alkylidenecycloalkanes;
- ❖ describe the conformational chirality in biphenyls and bridged biphenyls;
- ❖ explain the planar chirality in cyclophanes and ansa compounds;
- ❖ define and explain helicity and cyclostereoisomerism; and
- ❖ describe the stereochemistry of adamantanes and catenanes.

4.2 STEREOCHEMISTRY OF ALLENES AND SPIRANES

You have read that a compound is chiral if it is not superimposable on its mirror image. This definition provides a necessary and sufficient condition for chirality. You know that the chiral molecules may possess a rotation axis, but no plane of symmetry, centre of symmetry or alternating axis of symmetry. This criterion may be fulfilled by the presence of an asymmetric carbon atom or stereogenic centre. However, in this unit you will study about molecules that do not have stereogenic centres but still show optical isomerism.

Many organic compounds lack asymmetric carbon atom but possess axial, planar or helical chirality. In other words, these compounds are chiral molecules without chiral centres. The allenes, spiranes and many others are the examples which belong to this class of compounds. You will study about these compounds in the forthcoming sections. We will start with allenes, before that let us understand the principle involved in the axial or planar chirality. This can be explained by an elongated tetrahedron approach.

Elongated Tetrahedron Approach

You are very well familiar with the tetrahedral structure of hydrocarbons. A tetrahedral molecule has four atoms or groups at the corners of a regular tetrahedron and a tetra coordinated carbon in the centre. This can be represented in a generic form as Cabcd Fig. 4.1(a). If the carbon centre is replaced by a linear chain such as C-C or C=C=C, the tetrahedron becomes elongated along this axis as shown in Fig. 4.1(b). This leads to dissymmetry in

the molecule as a consequence of the formation of a chiral axis if the substituents are in accordance with the rules of chirality.

The reason for the dissymmetry is that the groups a and b at one end of the system lie in a plane at right angles to those at the other end.

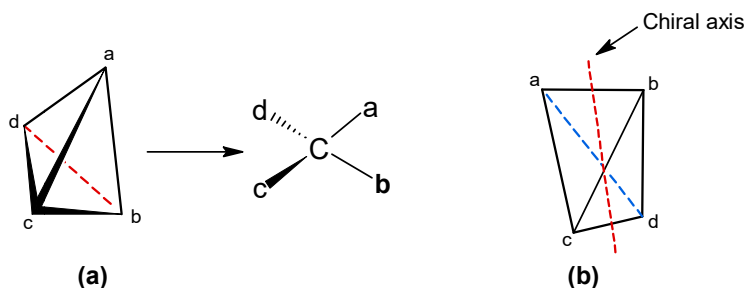


Fig. 4.1: (a) A regular tetrahedron (b) An elongated tetrahedron.

The explanation of existence of chiral axis by elongated tetrahedral approach is applicable to the allenes as you would read in the following subsection.

4.2.1 Stereochemistry of Allenes

The C=C=C system as mentioned above is called an allene. We can say that allenes are compounds in which a carbon atom is bonded to two other carbon atoms by double bonds. The simplest allene is propa-1, 2-diene $\text{H}_2\text{C}=\text{C}=\text{CH}_2$ which is isomeric with propyne. The bonding in allenes can be represented as given in Fig. 4.2. You would observe that the terminal carbons in the molecule are sp^2 hybridised and use the three hybridised orbitals to form a σ bond with two hydrogens and a carbon. The central carbon is sp hybridised, attached to two carbon atoms through these orbitals forming σ bonds. The central carbon has two p -orbitals which are involved in π bonding.

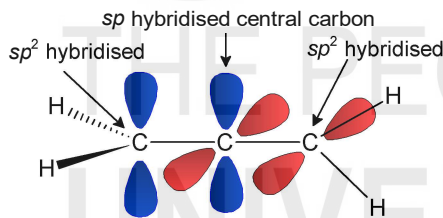


Fig. 4.2: Bonding in allenes.

You will also note that there is no conjugation between the π bonds. The two π bonds are perpendicular to each other. The two hydrogen atoms at each terminal carbon have a bond angle, HCH of 120° , and these three atoms lie in a plane. The two HCH planes are at right angles to each other which lie in orthogonal planes and can be represented as shown in Fig. 4.3(a). It can be represented in two dimension as shown in 4.3(b) and by the Newman projection as shown in Fig. 4.3(c).

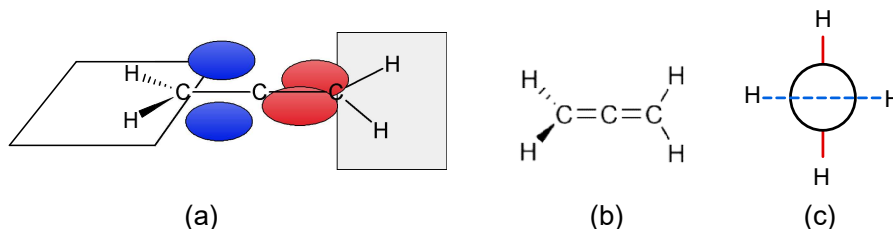


Fig. 4.3: Dissymmetry in allenes: Two mutually perpendicular pi bonds.

We can understand the enantiomerism in substituted allenes considering the example of 1,3-dichloropropa-1,2-diene. The molecule does not seem to be

consisting of a stereogenic centre. However, it does exist as an enantiomer as can be seen by the two structures shown in the figure 4.4(a) and (b) as mirror images. If we rotate structure 4.4(b) by 180° along the axis as shown, 4.4(c) is obtained which is not superimposable with 4.4(a). We observe that 4.4(b) is not superimposable on 4.4(a) by any other rotation. We conclude that 1,3-dichloropropa-1,2-diene is a chiral molecule due to the presence of a chiral axis and can exist as a pair of enantiomers, 4.4(a) and (b). It can be represented in Newman projection as shown in Fig. 4.4 (d).

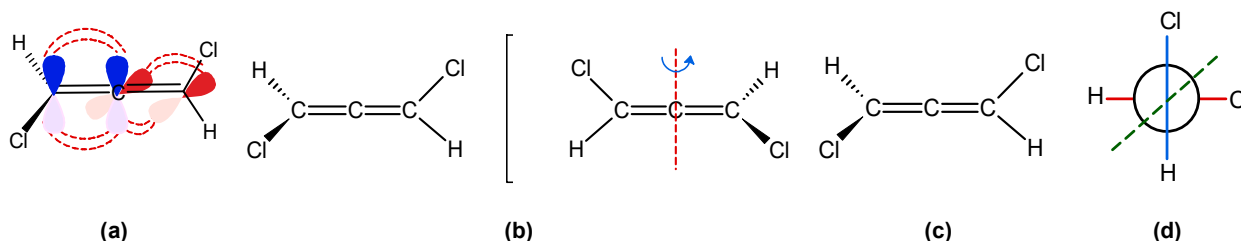


Fig. 4.4: 1,3-Dichloropropa-1,2-diene and its enantiomers.

Thus, we can conclude that any allene with two different substituents, for example, $abC=C=Cab$ will be chiral and can exist in two enantiomeric forms. When assigning the *R* and *S* configuration to allenes or other compounds with chiral axis or having axial chirality, the prefix 'a' is sometimes used to distinguish axial chirality from the other types. Thus, we may write **aR** or **aS** (with *P* and *M*) denoting a particular configuration. You will learn to assign the configuration in allenes as detailed below.

Assigning Configuration in Allenes

In order to assign the configuration to molecules with axial symmetry another sequence rules is applied (in addition to the sequence rules for assigning configuration as *R/S* which you have studied in your UG courses). The rule is that '**the near groups precede far groups**'. Let us make it more clear by taking 1-bromo-1-chloro-1,2-butadiene as an example which contains different groups attached to each carbon. The structure is given in Fig. 4.5.

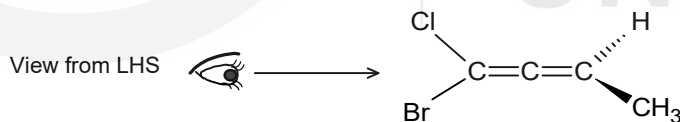
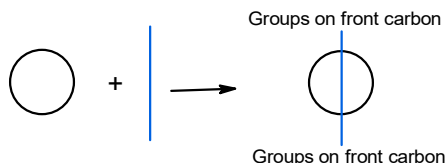


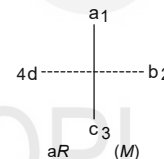
Fig. 4.5: 1-Bromo-1-chloro-1,2-butadiene structure (view from LHS).

You know that the molecules can be viewed from any side of the axis to assign the configuration. In the above example we have chosen to view from the left side initially as shown in the figure. You should follow the following steps in order to achieve the correct configuration.

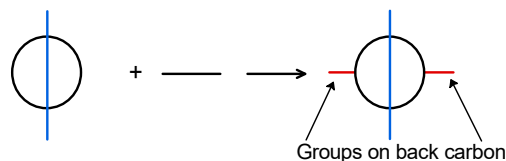
1. Draw a circle to achieve Newman projection to place the groups on the front and the back carbon. Now draw a vertical line on the circle which shows the groups attached to the front carbon as indicated below.



P designation in configuration is equivalent to *R* (priority order is clockwise) i.e., 1 to 3. If the priority order is anticlockwise, it is assigned *M*, equivalent to *S*.

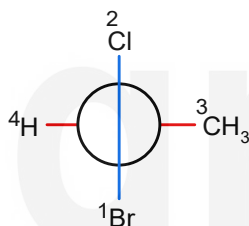


2. Draw a horizontal line behind the circle so as to show the groups on the back carbon as indicated below.

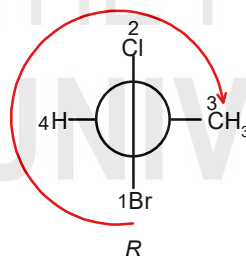


3. Place the groups as viewed in step 1 for the front carbon i.e., Cl on the top and Br on the lower side whereas on the back carbon, H and CH₃ are on the left and right sides respectively.

Now assign the priorities to the substituents as per CIP rules and the additional rule mentioned above. Priorities 1 and 2 are assigned to bromine and chlorine, respectively being present on the front carbon and priorities 3 and 4 are assigned to methyl group and hydrogen present on the back carbon.

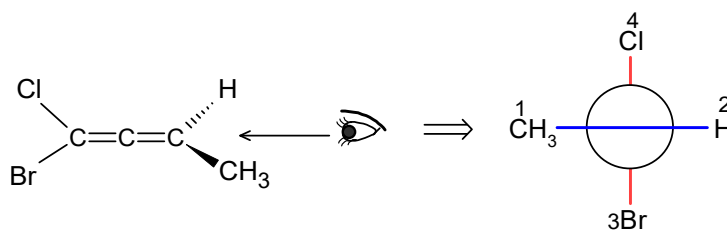


4. Look for the sequence 1, 2, 3 and observe. You will find it to be in clockwise direction therefore, it is assigned *R* configuration as can be seen in the structure given below.

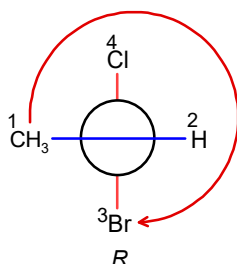


Now we will see whether the absolute configuration depends on the direction, the molecule is viewed, or it does not depend! It can be understood by viewing the same molecule through the C=C=C axis from the right hand side.

It can be seen from the structures drawn below that the horizontal line is in the front and the vertical line on the back side. On the front line, the groups attached are methyl on the left and hydrogen on the right side, while chlorine is on the top and bromine on the lower side on the vertical line. The priorities are assigned according to the rules and as indicated below.



After assigning the priorities of the groups attached, we find that the sequence 1, 2, 3 is clockwise. Thus, it is the *R* configuration as assigned in step 4. It can be verified from the structure drawn below.



It can be generalised from the above observations that a substituted allene, $abC=C=Cab$ will be chiral if $a \neq b$.

Further it can be seen that we obtain the same configuration when a particular enantiomer is viewed from any side of the chiral axis. Let us have a general example where *a* is the group of higher priority than the group *b*, Fig. 4.6, we arrive at *S*- configuration when the molecule is viewed from either direction.

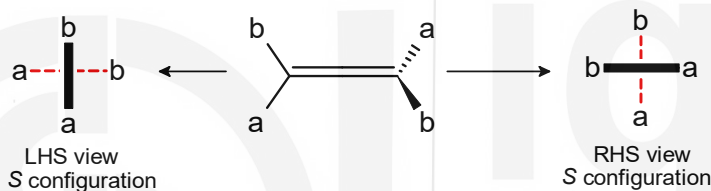


Fig. 4.6: Configuration in allenes with LHS and RHS views.

Thus, even when $a = c$ and/ or $b = d$, the framework retains chirality (*cf.*, elongated tetrahedral approach figure). Following this condition you can well understand and visualise that allene **A** is chiral but allene **B** is achiral as depicted in Fig. 4.7.

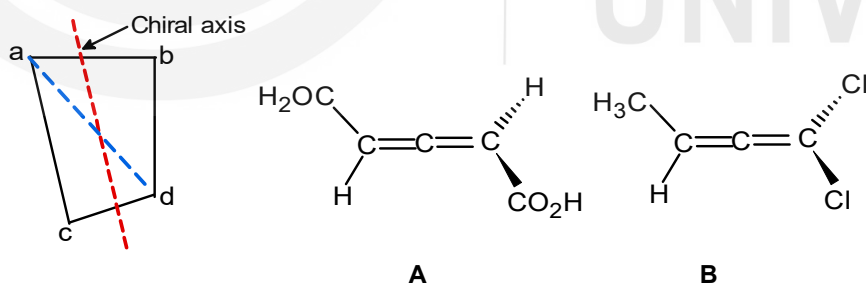


Fig. 4.7: Chiral axis and chirality in allenes

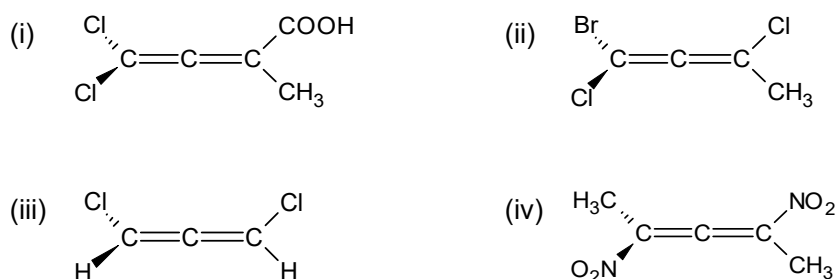
Let us now study another category of compounds that are optically active without the presence of a chiral centre but depict axial chirality and therefore become optically active. Before proceeding, try to answer the following SAQs.

SAQ 1

Show that penta-2,3-diene is a chiral molecule. Write any one of its enantiomer and determine the absolute configuration.

SAQ 2

Which of the following allenes would show enantiomerism?



4.2.2 Stereochemistry of Spiranes

You know that allenes have consecutive double bonds. When we replace the double bonds with two rings it leads to a bicyclic molecule. These are called the **spiro compounds** or the **spiranes** having one carbon atom common to two rings. Let us first understand the nomenclature of spiranes.

Nomenclature of Spiranes

The name 'spirane' comes from the Latin *spira* meaning twist. The twist is responsible for nonplanarity in the molecule and gives rise to the chirality. This can be observed in Fig. 4.8.

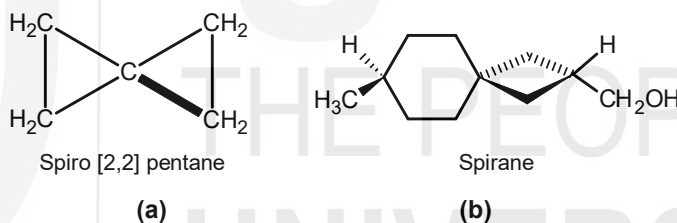


Fig. 4.8: a) A simple spirane b) A substituted spirane

The spiranes are named by selecting the parent or the root name which is given by counting the total number of carbons in the two rings and one carbon atom at the junction. Let us consider spiro-pentane which has 5 carbon atoms present in it as is indicated in Fig. 4.8 (a). The number of carbon atoms in the two rings (without counting the carbon atom common to the two rings) is placed in square brackets where the lower number is written first followed by a dot, then the other number is written. In the case of spiro-pentane we have two rings, each consisting of two carbon atoms leaving aside the one shared by both the rings therefore, we will write [2.2]. The prefix 'spiro' is written before the bracket. Thus, for this simple spirane we write its name as spiro [2.2]-pentane. Some more examples of unsubstituted spiranes are given in Fig. 4.9.

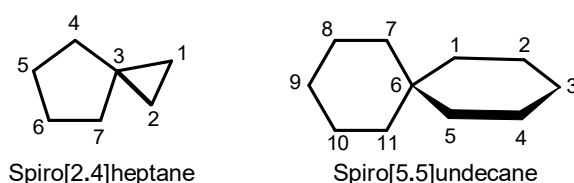


Fig. 4.9: The unsubstituted spiranes.

In substituted spiranes, the position of the substituents is indicated by the numbers. The numbering begins with the smaller ring and passes through the Junction or the common carbon atom; the numbering is continued on to the bigger ring. For example, for a substituted spirane, the structure given in Fig. 4.10 is named 1-chlorospiro [3.5] nonane.

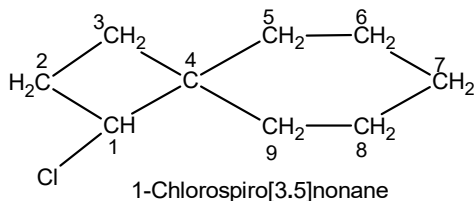


Fig. 4.10: Naming a substituted spirane.

The conditions for chirality in spiranes are similar to those of allenes. The two rings of spiranes are perpendicular to each other and different substituents on the carbon atoms in each ring will make the molecule chiral. Thus suitably substituted spiranes can exhibit enantiomerism if these possess axial chirality.

These enantiomers are also assigned the absolute configuration following the method used in the case of allenes. The enantiomer of a molecule shown in Fig. 4.11 is found to possess *R*-configuration.

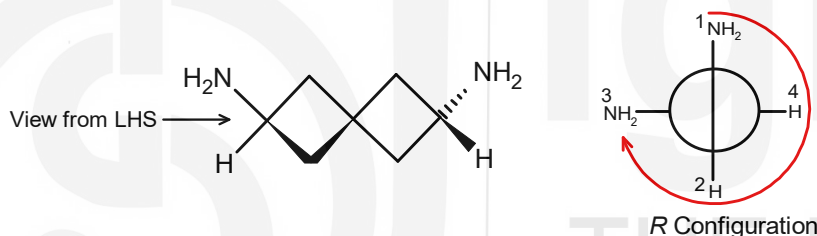


Fig. 4.11: Assigning absolute configuration in spiranes.

A spiro compound may also contain asymmetric carbon atoms as substituents or as part of the ring. For example, structure (I) given in Fig. 4.12 has two similar asymmetric carbon atoms marked with an asterisk (*). It will have three differential geometrical isomers viz., II, III and IV. Further, each of these geometrical isomers will exist as a pair of enantiomers.

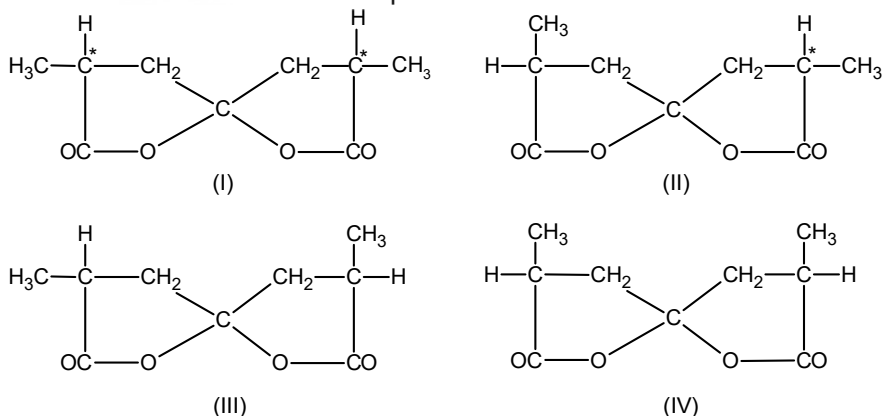


Fig. 4.12: Geometrical isomers in spiranes with asymmetric carbon.

Now we would study another type of molecules that have axial chirality viz., alkylidenes or alkylidenecycloalkanes.

4.3 STEREOCHEMISTRY OF ALKYLIDENE-CYCLOALKANES

You know that a ring and a double bond are stereochemically equivalent, there is a possibility of replacing the double bond by a ring that could be of any size. The replacement of double bonds in allene by a cycloalkane ring gives the alkylidenecycloalkane. This replacement does not change the basic geometry of the molecule. A general structure with substituents is shown in Fig. 4.13(a). As can be seen from the structure, these molecules have an exocyclic C=C double bond and are configurationally stable.

If the alkylidene cycloalkane molecule is suitably substituted it will show optical activity and exist as enantiomers. The substituent groups are present in planes perpendicular to each other. This leads to the presence of chiral axis as discussed in the case of allenes and spiranes. Thus, 4-methylcyclohexylidene acetic acid exists as two enantiomers as shown in Fig. 4.13(b).

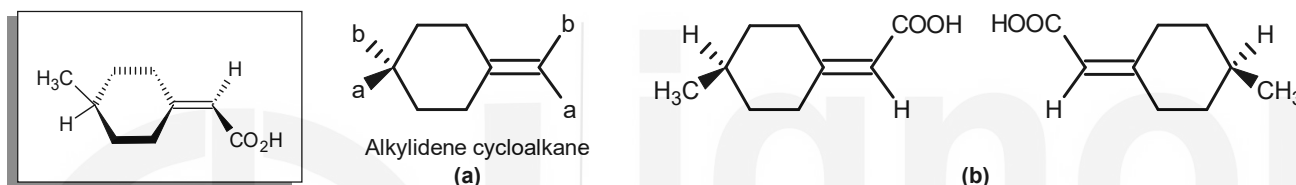


Fig. 4.13: (a) Structure of general alkylidenecycloalkane (b) Enantiomers of 4-methylcyclohexylidene acetic acid.

The chiral activity as depicted above is also observed in those compounds where one carbon in C=C is replaced by a hetero atom like N. Thus, an exocyclic imine bond, C=N, has the unshared pair of electrons that acts as a substituent and results into an optically active compound with two enantiomers. The stability of the isomers depends upon the substituent attached to the N in imine. For example, imines with alkyl group are configurationally unstable and racemisation occurs readily. On the other hand, presence of a hydroxy group i.e., in oximes, resolvable and configurationally stable molecules are obtained. The structures of the imines and the oximes are given in Fig. 4.14.

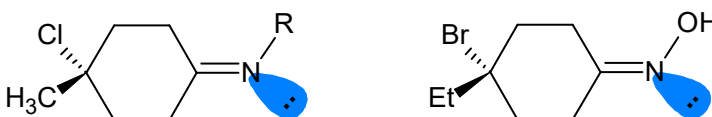
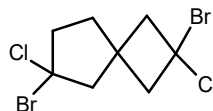


Fig 4.14: Chiral imines and oximes.

We would next discuss the stereochemistry of biphenyls which also exhibit axial chirality but by virtue of restricted rotation around a single bond. First try to answer the following SAQ.

SAQ 3

Draw the enantiomers of the spirane molecule structure given below.



4.4 STEREOCHEMISTRY OF BIPHENYLS

You studied about the presence of asymmetry due to the presence of chiral axis in case of allenes, spiranes and alkylidenecycloalkanes as a result of restriction of double bonds, two rings arranged in perpendicular fashion and the presence of a ring and double bond both, respectively. Now you will observe the presence of chirality in molecules due to hindered rotation about single bonds. This type of behaviour is exhibited in case of biphenyls or biaryls. As in the case of molecules dealt in the previous sections, the chirality is observed in biphenyls if they are appropriately substituted. The names given generally to isomers so derived are '**atropisomers**', and the phenomenon is called '**atropisomerism**'. Let us understand the phenomenon in biphenyls.

4.4.1 Atropisomerism: Conformational Chirality

The term *atropisomerism* is taken from the German literature meaning, '*no rotation*' and derived from Greek word '*atropos*' which means '*without turn*'. The restricted rotation is due to the different spatial arrangements of the groups. It was first detected in compounds of biphenyl series. Biphenyls are compounds which contain two aromatic rings joined together by a carbon-carbon single bond both of which are sp^2 hybridised as shown in Fig. 4.15(a). There is usually free rotation about the C1-C1' bond joining the two rings and it is also called the **pivotal bond** (Fig. 4.15b).

Atropisomerism is the optical isomerism or enantiomorphism that includes stereoisomerism due to restricted rotation about single bond.

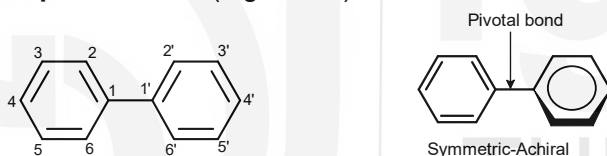


Fig. 4.15: (a) Biphenyl structure (b) Biphenyls showing pivotal bond.

When the four ortho positions are substituted by bulky groups, biphenyls show optical activity. This is because the rotation about the central bond does not occur (due to steric hindrance), and the two rings lie in different planes, i.e., the two rings are inclined to each other. In fact, the actual angle of inclination of the two rings depends on the substituent groups, but it is usually about 90° , i.e., the two rings are approximately perpendicular to each other. Such a molecule is not superimposable on its mirror image, and therefore, it will be optically active. The rotational isomerism of biphenyl derivatives as shown in Fig. 4.16, leads to the formation of enantiomers when $a \neq b$ and $c \neq d$ as it forms the chiral axis. It is often also called *biphenyl isomerism*. Thus, atropisomerism is a type of conformational (rotational) isomerism in which the conformational isomers or conformers can be isolated.

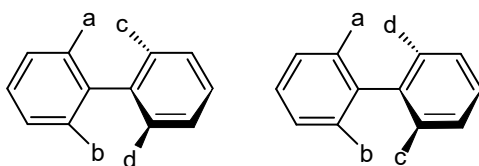


Fig. 4.16: Enantiomers of a chiral biphenyl derivative.

If we consider a biphenyl with substituents as a,b on both the rings, the energy profile diagram for a 360° rotation around the bond between two phenyl rings can be represented as shown in Fig. 4.17.

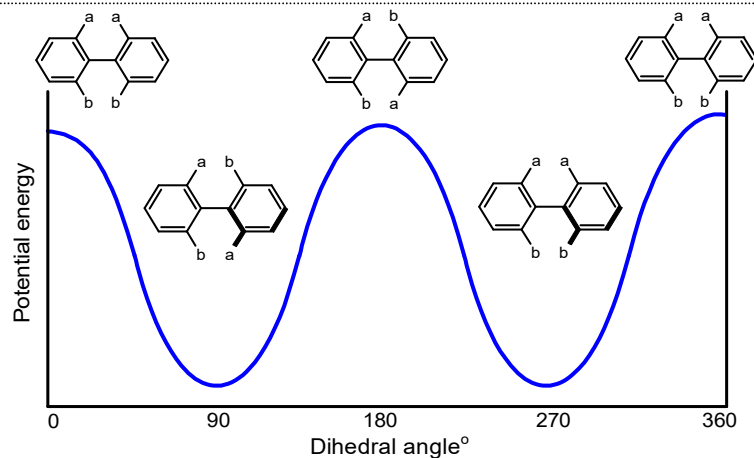
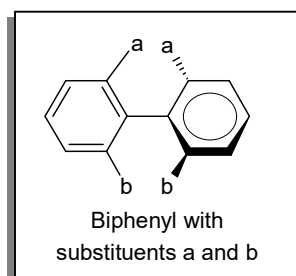


Fig. 4.17: Energy profile diagram for rotation in the bond between two phenyl rings.

In the following subsection, let us understand the optical activity in biaryls.

4.4.1 Optical Activity in Biaryls

As per the discussion given in the above subsection, it can be concluded that 2,2',6,6'-biphenyls can be chiral if the following conditions are met.

- The biphenyls must contain bulky ortho substituents of the size so that the rotation around the single bond that connects the aromatic rings is restricted due to the 'collision' of substituents as depicted in Fig. 4.18.

Resolvable means that the compound is optically active.

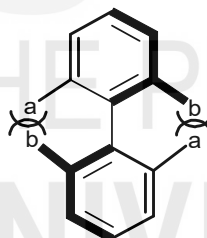


Fig. 4.18: Structure of a biphenyl with bulky groups.

- If the substituents are not bulky enough, the rotation is possible around the single bond and the molecule attains a co-planar conformation as shown in Fig. 4.19(a). The molecule has a plane of symmetry hence no chirality. These biphenyls are not resolvable also as these lack the formation of any enantiomers. Monosubstituted at the ortho positions having smaller substituents and dissymmetric biphenyls are invariably nonresolvable. The energy barrier to rotation increases when the size of the groups around the pivotal bond increases. Larger the substituent, the slower is the rate of racemization. For example, 2, 2'-difluoro-6,6'-dimethoxybiphenyl is non-resolvable. The order of steric hindrance produced by different groups is of the order:
Br >> Me > Cl > NO₂ > CO₂H >> OMe > F
- The biphenyls that contain two different ortho substituents on each ring are resolvable as the molecule becomes chiral and exists in enantiomeric forms. Obviously if one, or both, rings contain two identical substituents, i.e., X=Y in Fig. 4.19(a) the molecule is not chiral.

Observe the structure of substituted biphenyl namely, 6,6'-dinitrodiphenic acid as given in Fig. 4.19(b). The molecule is represented in a key conformation with the two aromatic rings mutually perpendicular. This molecule is chiral as in this molecule the mirror image is not superimposable on each other and hence, are enantiomers. As seen, in this molecule, there is no chiral centre. In fact, it is the molecule as a whole that is chiral due to restricted rotation. As mentioned above, this is called as **atropisomerism or conformational chirality**.

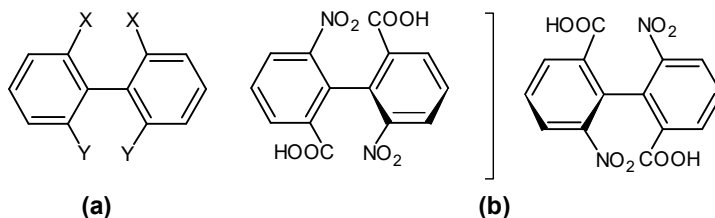


Fig. 4.19: (a) Coplanar conformation in biphenyls
(b) 6,6'-Dinitrodiphenic acid and its mirror image

Let's assign the configuration to one of the enantiomers of this compound as explained in Fig. 4.20(a). On viewing the molecule from the left side of the chiral axis we obtain Fig. 4.20(b) and on giving the priorities we find it to possess *S*-configuration.

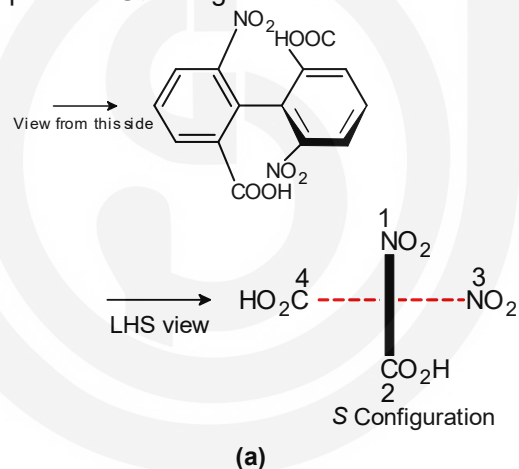


Fig. 4.20: (a) Structure of 6,6'-Dinitrodiphenic acid
(b) Assigning absolute configuration to 6,6'-Dinitrodiphenic acid

Buttressing effect

Another observation can be made by substituting another group at the meta position of the ring. The substituent pushes the substituent at the ortho position towards the connecting bond between the two rings. This increases the steric repulsion between the ortho substituents on two rings and the energy barrier for racemisation results. For example, introduction of an ethyl group at the *meta* position in 2, 2'-bis(trifluoromethyl)biphenyl, Fig. 4.21(a) increases energy barrier by 12 kJ/mol for this molecule as compared to the only *ortho* substituted biphenyl. This is called the **buttressing effect**.

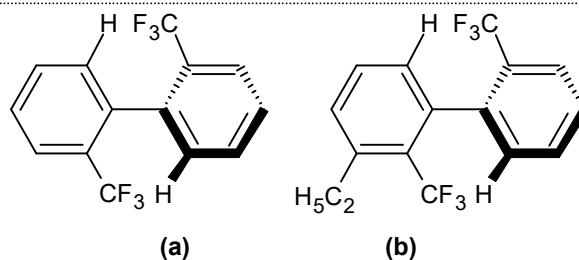


Fig. 4.21: (a) Structure of 2, 2'-bis(trifluoromethyl)biphenyl; (b) Ethyl substituted 2, 2'-bis(trifluoromethyl)biphenyl.

You read above that almost all the appropriately ortho substituted biphenyls are resolvable. There is another way that leads to resolvable molecules. Let us understand how?

4.4.2 Stereochemistry of Bridged Biphenyls

You have read about bridged compounds while studying chemistry of hydrocarbons. We can define the bridged compounds as the polycyclic compounds in which two rings have two or more atoms in common and these atoms form a bridge between the rings. The bridged bicyclic compounds like the biaryls, have a bridge of atom(s) placed across from one side of the ring to the other ring.

You have read in the previous paragraph that the conformational stability of biaryls is dependent upon the bulkiness of the ortho-substituents on both the rings. When 2, 2'-positions of a biphenyl derivative are joined/bridged, the possibility of stable chiral conformation is dependent on number of bridging atoms and presence of substituents at the other two ortho positions, namely at 6 and 6'-positions. In other words, it depends strongly on the ring size and bulkiness of the ortho-substituents and therefore rigidity of bridges. The stereochemistry of biphenyls having 2,2'-bridge has been studied by UV and NMR spectroscopy and X-ray analysis. It has been found to affect the optical activity of these compounds. When $n = 1$ i.e. one bridge is joined to 2,2' positions and the biphenyl molecule is disubstituted, we get a disubstituted fluorene. In this molecule the biphenyls remain almost planar therefore, it is not resolvable. When $n = 2$, we get disubstituted molecule of 9,10-dihydrophenanthrene. This compound can be resolved. The compounds with three atom bridges can be resolved and are optically stable.

When the number of bridging atoms are three or more, the configurational stability is comparable with biaryls without bridges.

As can be observed by the examples given above, the shortening of the length of a biaryl bridge considerably decreases conformational stability. Therefore, the axially chiral biaryls having a five-membered bridge rapidly racemize at room temperature. It was found that enantiopure sample of the tetra-*ortho*-substituted biaryl, Fig. 4.22, racemizes at room temperature even under neutral conditions. It has been attributed to a low rotational energy barrier of 99 kJ/mol. The biaryl has a formyl and a hydroxyl group in opposite aryl rings and forms an intermediate five-membered lactol ring, which reduces both the torsion angle between the two aryl rings and the barrier to rotation about the chiral axis.

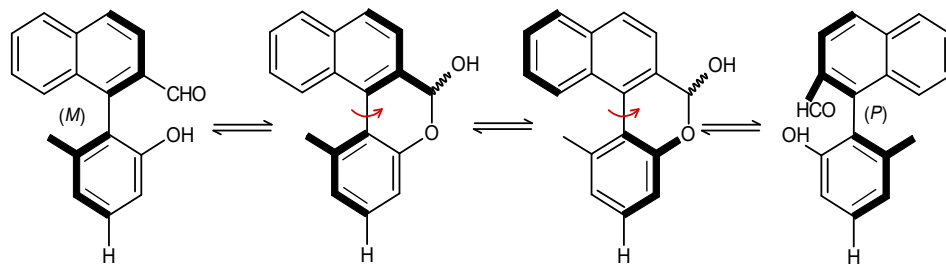


Fig. 4.22: Tetra-ortho-substituted biaryl.

The rotational energy barrier of biaryls can be increased by introduction of a rigid nonplanar bridge. Thus, in a binaphthyl derivative with phosphorous bridging atom, the racemization energy is low (60 kJ/mol). For larger bridges, as the dihedral angle increases, the two aryl rings adopt nonplanar chiral conformation. The configurational stability is enhanced when the other two ortho substituents are substituted with bulky groups. Some chiral bridged biphenyls are given in Fig. 4.23.

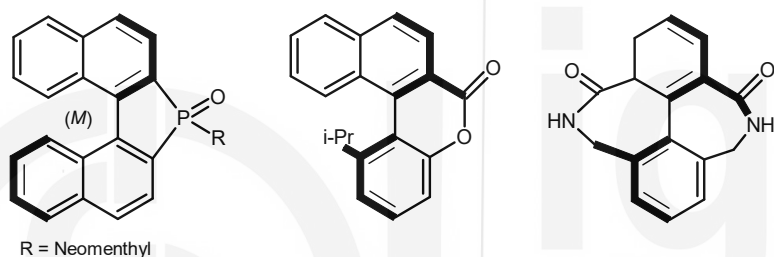


Fig. 4.23: Chiral bridged biphenyls

In the following section, let us understand the stereochemistry of molecules with planar chirality. Before you proceed further, try to answer the following SAQ.

SAQ 4

Draw the structure of 2,2'-difluoro-6,6'-dimethoxybiphenyl-3,3'-dicarboxylic acid and predict whether the molecule is optically active or not?

4.5 PLANAR CHIRALITY

As mentioned earlier, planar chirality is also due to the presence of a nonchiral carbon in the molecule. The planar chirality is shown by a molecule with asymmetry in the molecular plane. The chirality is particularly due to the out of the plane arrangement of atoms or groups in the molecule with respect to reference plane, hence called chiral plane. As in the case of chiral axis the chirality arises due to the exchange of groups around the axis, similarly the exchange of substituted groups across the plane lead to planar chirality. The definition of planar chirality was proposed by Cahn et al. in 1956. A chiral plane contains as many atoms in the molecule as possible but not all. The chirality is due to the fact that at least one or more group(s) is/are not contained in the chiral plane or the stereoplane. Certain ansa compounds, paracyclophanes, trans-cycloalkenes with a twisted double bond, and metallocene complexes have a chiral plane. Among molecules with planar chirality, the cyclophanes are the most important. Other examples are bridged

If a plane of symmetry develops chirality only by the difference of both sides of the plane, it leads to planar chirality.

annulenes, trans-cyclooctene, and related molecules, which may alternatively be considered to possess axial chirality and metallocenes and other metal complexes of arenes. We will consider the stereochemistry of some of the molecules belonging to this category.

4.5.1 Cyclophanes

Cyclophanes are the compounds in which two benzene rings are joined by methylene bridges on either side between para positions or meta positions giving paracyclophanes and metacyclophanes respectively, Fig. 4.24 below.

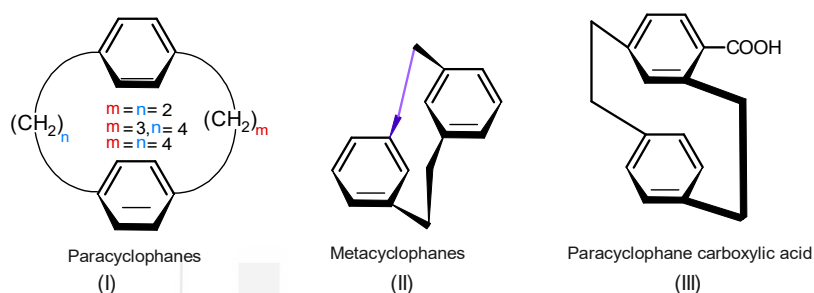


Fig. 4.24: Structures of metacyclophanes and paracyclophanes.

Paracyclophane with $m = n = 2$ is optically stable. If $m = 3$ and $n = 4$, the compound is resolvable but racemises at 150–160 °C. However, if both m and n are 4, the compound cannot be resolved. In [2.2] paracyclophane derivative the chiral plane is the plane of the benzene ring. In paracyclophanes that are substituted at one ring, the presence of even one substituent in any of the benzene rings makes the structure chiral. Some examples with the substitution of one of the benzene rings with the COOH group are given in Fig. 4.25.

Metallocenes are organometallic compounds in which a metal atom is sandwiched between two aromatic rings, for example, ferrocene.

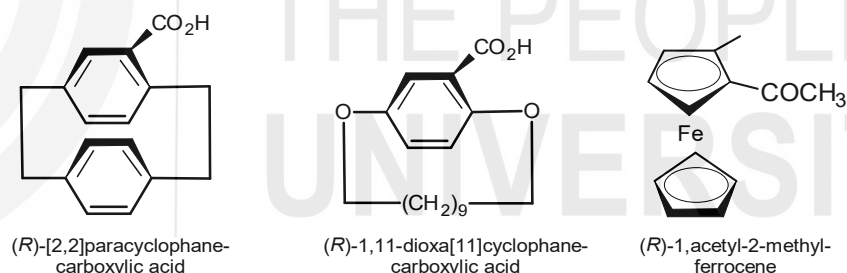


Fig. 4.25: Molecules with chiral planes.

4.5.2 Ansa Compounds

The carbon-bridged analogues of benzene rings are known as ansa compounds (ansa = Latin for handle). Ansa Compounds constitute a subclass ofphanes, where two nonvicinal positions of an aryl ring are substituted with hetero-atoms and which in turn are cojoined by a bridge.

As in the case of substituted biphenyls, the restricted rotation of benzene ring is responsible for their chirality provided these are appropriately substituted. Thus, as an example, compounds (a) and (b) in Fig. 4.26, having two ortho substituents and a ten-membered methylene bridge are optically stable. When $Y=H$ and $n = 10$, then the ansa-compound becomes nonresolvable, i.e., the optical activity disappears as in the case of (c). It is due to low energy barrier and rapid rotation of the phenyl ring through the large dioxamethylene chain. This finally results into racemisation. The compound (e) with an eight-

numbered methylene bridge can be resolved and is optically stable. However, when there is only one substituent with a nine membered bridge, the compound is of intermediate optical stability as in the case of (d)(Fig. 4.26).

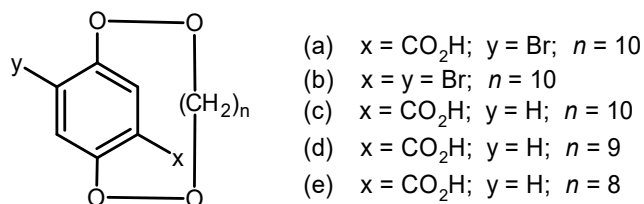
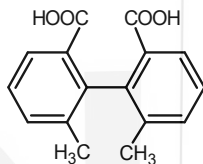


Fig. 4.26: Some examples of ansa compounds.

Now we will discuss a special case of chiral axis called helicity. Before proceeding to the next section try to answer the following SAQ.

SAQ 5

Given below is a biaryl compound. Are the two benzene rings supposed to be in a plane? Draw the structure to justify your answer.



4.6 HELICITY

Several compounds have been prepared that are chiral because they have a shape that is actually helical and can therefore be left handed or right handed in orientation. A helix, like the thread of a screw, can turn two ways. The two helical structures arise due to the possibility of two turns. The resulting structures are non-super imposable mirror images of one another. Some common objects having helical geometry are shown in Fig. 4.27.

The helical molecules are optically active due to the presence of **helical dissymmetry** or **helicity**. In fact, helicity is a particular type of chirality.

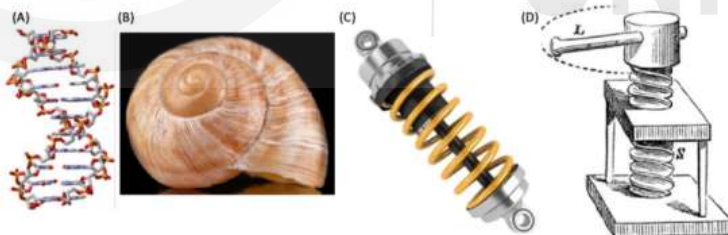


Fig. 4.27: Some common objects having helical geometry.

Thus, molecules with helical structures also exhibit chirality which is due to the presence of a chiral plane. You might be familiar with right-handed double helical structure of DNA. We can say that **helical molecules** are those molecules in which the arrangement of the atoms or groups is an imaginary helix. Sometimes the entire molecule is usually less than one full turn of the helix, but this does not alter the possibility of left and right handedness. An example is hexahelicene, in which one side of the molecule must lie above the other because of crowding. The planar configuration of helicene is not possible owing to severe steric interactions between the terminal rings. Based on the

name helicenes, molecules with chiral planes are also called compounds with **helical chirality**.

Hexahelicene is a classic example of a stable helical molecule with a high optical rotation. A number of aromatic rings are joined in ortho junction to form a helical type of structure. Stereoisomerism is possible in helicenes having a minimum of 5 benzene rings. Helicenes having a larger number of benzene rings (7, 8 or 9) are also known. Such compounds are optically active since these have no elements of symmetry; and can have left- or right-handed orientation. A right-handed helix is described as *P* and a left-handed one as *M*. See Fig. 4.28. The helicenes can be racemised by heating above their melting points. The heterocyclic analogues of hexahelicene in active forms have also been prepared.

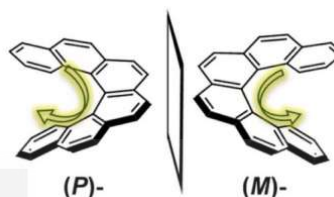


Fig. 4.28: Structure of hexahelicene.

In the following section you will study the stereoisomerism in cyclic compounds.

4.7 CYCLOSTEREISOMERISM

When the chiral centres are present in cyclic molecules, it is called the cyclosteroisomerism. In monocyclic molecules with a single achiral substituent the σ plane passes through the substituent and the carbon of the cyclic molecule, in one of the conformations. As a result, it behaves as a *meso* isomer. An example of this type is bromocyclopentane. Similarly, the monocyclic molecules with two or four achiral substituents present at diagonally opposite carbon atoms exist in their *meso* form as *cis* and *trans* isomers. The 4-*t*-butylcyclohexanols exhibit this kind of nature as can be seen in the Fig. 4.29.

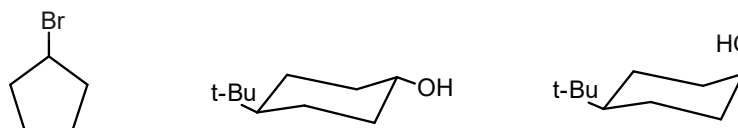


Fig. 4.29: Cyclic achiral, *meso* isomers.

If the symmetry elements σ /*i*/ S_n are absent in monocyclic molecules, these can exist in enantiomeric forms. Two examples are given below in Fig. 4.30.

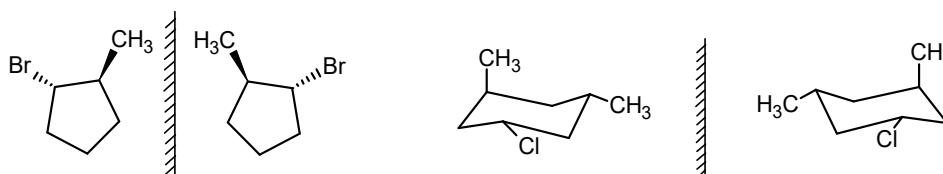


Fig. 4.30: Cyclic chiral molecules.

Small-bridged compounds have fewer stereoisomers despite completely dissymmetric nature and absence of the symmetry elements σ /*i*/ S_n . The reason is steric, as the *trans*-ring fusion at the bridgeheads is impossible due

to involvement of very high energy species. Thus, bicyclo[2.2.1]heptan-2-one has two chiral centres, but due to the lack of any achirotopic centre, the molecule has only 2 stereoisomers and not 4, as can be expected on the basis of presence of two chiral centres. The stereoisomers are shown in Fig. 4.31.

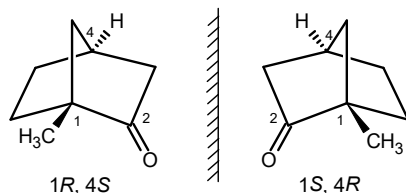


Fig. 4.31: Stereoisomers of bicyclo[2.2.1]heptan-2-one.

In the following section you will briefly study about the stereochemistry of large fused cyclic molecules.

4.8 STEREOCHEMISTRY OF ADAMANTANES

Adamantane is a tricyclic system having three cyclohexane rings fused together, therefore also named tricyclo [3.3.1.1] decane. Its molecular formula is $C_{10}H_{16}$ and it is colourless, crystalline having a camphor-like odour. It is an unfunctionalised hydrocarbon which means the molecule is composed of only carbon and hydrogen. It has wide applications and was first isolated from a high boiling fraction of petroleum. Its structure is similar to hexamethylene tetramine with four nitrogens replaced by CH. The 16 hydrogen and 10 carbon atoms can be described by only two sites, 4 equivalent sites and 6 equivalent sites as can be seen in the structure of the molecule given in Fig. 4.32. These are depicted in the structure by nos. 1 and 2.

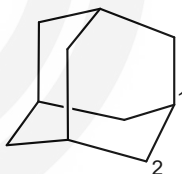


Fig. 4.32: Structure of tricyclo [3.3.1.1] decane.

Let us summarise the key concepts studied in this unit.

4.9 SUMMARY

There are some complex systems which do not have a chiral centre but the presence of a chiral axis or a plane becomes one of the factors responsible for the optical activity of such molecules.

Allenes are compounds in which a carbon atom is bonded to two other carbon atoms by double bonds. Any allene with two different substituents, where, $abC=C=Cab$ will be chiral and can exist in two enantiomeric forms. When assigning the *R* and *S* configuration to allenes or other compounds with chiral axis or having axial chirality, the prefix 'a' is sometimes used to distinguish axial chirality from the other types. The assignment is done as per the CIP rules.

When the double bonds are replaced with two rings in an allene, it leads to a bicyclic molecule. These are called the spiro compounds or the spiranes having one carbon atom common to two rings. The spiranes are named by selecting the parent or the root name which is given by counting the total number of carbons in the two rings and one carbon atom at the junction. The suitably substituted spiranes can exhibit enantiomerism if these possess axial chirality. These enantiomers are also assigned the absolute configuration following the method used in the case of allenes.

The replacement of double bonds in allene by a cycloalkane ring gives the alkylidenecycloalkane. If the alkylidenecycloalkane molecule is suitably substituted it will show optical activity and exist as enantiomers. The substituent groups are present in planes perpendicular to each other.

The biphenyls exhibit the presence of chirality in molecules due to hindered rotation about single bonds. As in the case of Allenes, spiranes, and alkylidenecycloalkanes, the chirality is observed in biphenyls if they are appropriately substituted. The names given generally to isomers so derived are 'atropisomers', and the phenomenon is called 'atropisomerism'. When the four ortho positions are substituted by bulky groups, biphenyls show optical activity. When a group at the meta position of the ring is present, an increase in the steric repulsion between the ortho substituents on two rings is observed and the energy barrier for racemisation results. This is called the buttressing effect.

The planar chirality is also due to the presence of a nonchiral carbon in the molecule. It is shown by a molecule with asymmetry in the molecular plane. The chirality is particularly due to the out of the plane arrangement of atoms or groups in the molecule with respect to reference plane. Certain ansa compounds, paracyclophanes, *trans*-cycloalkenes with a twisted double bond, and metallocene complexes have a chiral plane.

Cyclophanes are the compounds in which two benzene rings are joined by methylene bridges on either side between para positions or meta positions giving paracyclophanes and metacyclophanes respectively. The carbon-bridged analogues of benzene rings are known as ansa compounds. Ansa compounds constitute a subclass of phanes, where two nonvicinal positions of an aryl ring are substituted with hetero-atoms and which in turn are cojoined by a bridge.

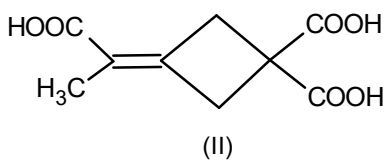
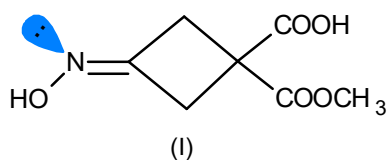
The molecules with helical structures also exhibit chirality which is due to the presence of a chiral plane. Based on the name helicenes, molecules with chiral planes are also called compounds with helical chirality.

When the chiral centres are present in cyclic molecules, it is called the cyclostereoisomerism. If the symmetry elements σ / i / S_n are absent in monocyclic molecules, these can exist in enantiomeric forms.

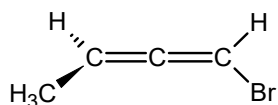
Adamantane is a tricyclic system having three cyclohexane rings fused together, therefore also named tricyclo [3.3.1.1] decane. It is an unfunctionalised hydrocarbon in which the molecule is composed of only carbon and hydrogen and has a T_d symmetry.

4.10 TERMINAL QUESTIONS

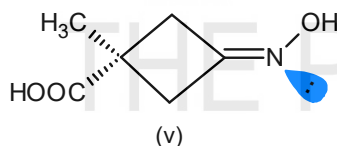
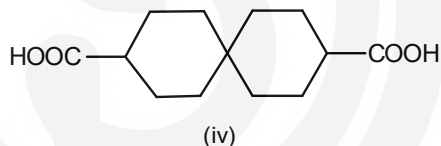
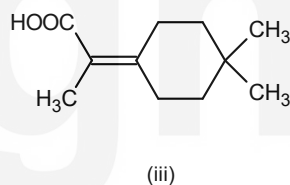
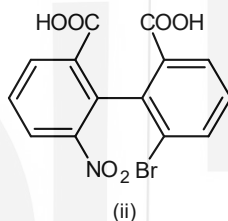
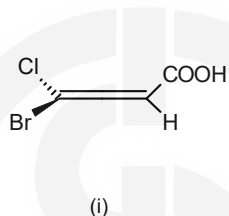
- Why do spiranes exhibit optical isomerism?
- Which of the following is a chiral molecule? Explain giving reasons.



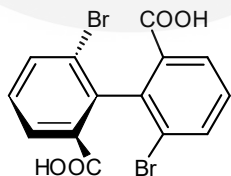
- Determine the absolute configuration of this molecule by drawing the Newman projection.



- Which of the following is/are nonchiral molecule(s)?



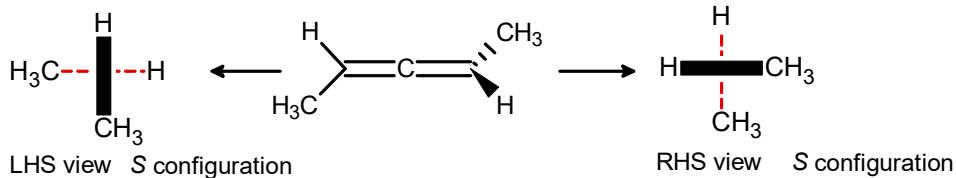
- Determine the absolute configuration of the molecule given below when viewed from LHS.



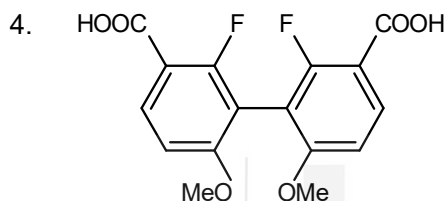
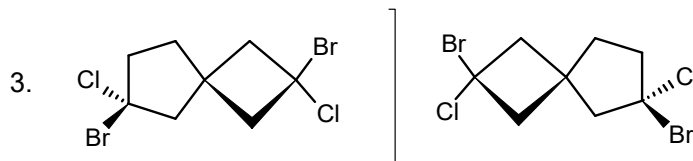
4.11 ANSWERS

Self Assessment Questions

- We see that the two substituents on each carbon of the allene system are different, hydrogen and methyl group, hence it will be a chiral molecule. One of its enantiomer is drawn as shown below. View from either side is represented as a cross of two lines and priorities are assigned. We find that this enantiomer has *S*-configuration.

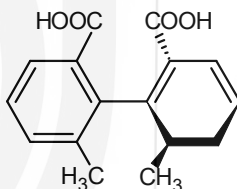


2. (ii), (iii) and (iv) are chiral molecules and will show enantiomerism.



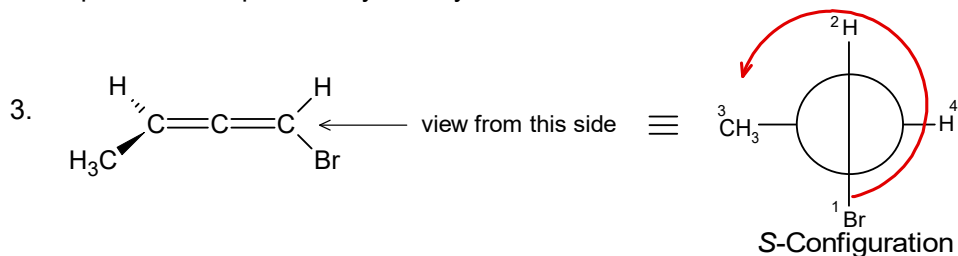
As can be seen the compound is not optically active due to small groups present in 2,2' and 6,6' positions.

5. The benzene rings are not in a plane as can be seen by the wedge structure drawn below. It can be drawn as its mirror image also.

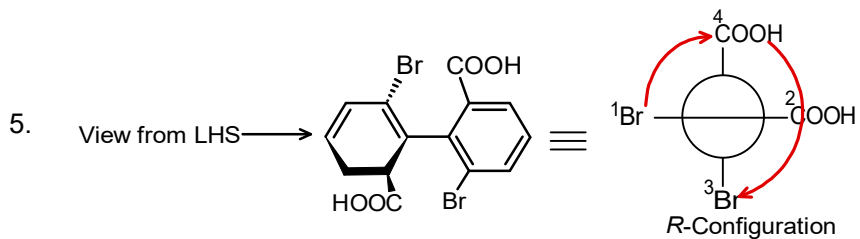


Terminal Questions

- Spiranes have two rings joined through a common carbon atom which makes these molecules nonplanar and the two rings cannot rotate about any axis. Hence they exhibit optical isomerism because of restricted rotation provided that they contain two different substituents on each ring.
- Compound (i) is chiral as it does not possess a centre, plane or alternating axis of symmetry. While compound (ii) is achiral as it possesses a plane of symmetry.



4. Only molecule (iii) is nonchiral.



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