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OPTICAL ROTATORY DISPERSION (ORD) and CIRCULAR DICHROISM (CD)

Light is electromagnetic radiation and is associated with electric and magnetic fields. The energies associated with electric and magnetic waves are equal. The discussion about the phenomenon like UV-visible, ORD and CD are concerned with electric field only.

In an ordinary light, the electric vector associated with the light wave oscillates in all directions perpendicular to the direction of propagation. If such unpolarised light is filtered inorder to remove all oscillations, other than in one direction, then the light is said to be plane polarized or more correctly linearly polarized. Thus linearly polarised light is defined as the electromagnetic radiation which contains an electric vector oscillating in one plane.

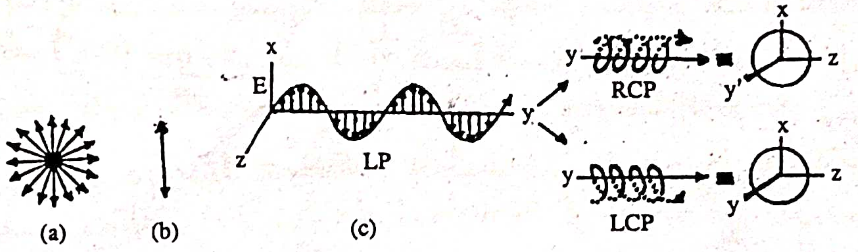


Fig. Linearly polarized light and circularly polarized rays: (a) Narrow beam of ordinary light; (b) A beam of plane polarized light; (c) Circularly polarized components of a linearly polarized light.

Circularly polarised light:

– A circularly polarised light is one in which the electric vector rotates uniformly about the direction of propogation by 2π radians during each cycle. Linearly polarized light can be regarded as the resultant of two equal and opposite beams of circularly polarized light. i.e., as a combination of left and right circularly polarized light.

– A left circularly polarized light is one in which the electric vector rotates uniformly in anticlockwise or left direction about the direction of propogation.

– A right circularly polarized light is one in which the electric vector rotates uniformly in clockwise direction about the direction of propogation.

If a linearly polarized light is passed through chiral compounds then they rotate the linearly polarized light either towards right or towards left. Such compounds are called as optically active compounds. Thus optical rotation refers to the ability of certain compounds to rotate the plane of polarized light.

Those compounds which rotate the plane polarized light towards right are called dextro-rotatory and those which rotate to left are called levorotatory.

The ~~spec~~ specific rotation $[\alpha] = \frac{100\alpha}{lc}$

where α is the observed rotation,
l is the length of polarimeter tube (in dm)
and c is the concentration (in g/100 ml).

The value $[\alpha]$ varies with temperature and with wavelength of light used and hence it becomes necessary to specify these values along with $[\alpha]$. Usually sodium D line [589 nm] is used for routine measurements. If optical rotation is observed at 20°C then the specific rotation is represented as $[\alpha]_D^{20}$.

This type of optical ~~rotation~~ rotation is observed for the compounds which contain a chiral centre (i.e. which is devoid of plane of symmetry).

UV-visible, ORD and CD spectroscopies fall into the ~~broad~~ broad classification called electronic absorption spectroscopy. UV-visible spectroscopy is the most common of these and is used to measure energy and intensity of ~~or~~ ordinary light absorbed by compounds. All these spectroscopic studies involve the same photophysical process – the promotion of an electron from the ground state orbital to an excited orbital. The difference is that the UV-visible spectroscopy measures the absorption of ordinary light, where as in ORD and CD spectroscopies measure the absorption of left and right circularly polarized light and displays the difference in their absorption. Finally it can be concluded that the light beam used in UV-visible spectroscopy is essentially unpolarised, and the light beam used in ORD and CD studies is essentially plane polarized. The optical techniques like polarimetry, ORD and CD which can differentiate between the two enantiomers of a chiral compound are called chiroptical techniques.

Optical Rotatory Dispersion:

When a light beam travels through a medium, two things happen as a result of the interaction between its electromagnetic field and the valence electrons of the medium.

1) The velocity of light (V) changes and with it, the refractive index (n)
[Refractive index is the ratio of velocity of light in vacuum to velocity of light in medium; $n=\frac{c}{V}$]

2) The intensity of the emergent light diminishes due to absorption.

Both the phenomena are interrelated and are contributions of electronic transitions and wavelength dependent.

When a beam of plane polarised light is passed through an optically inactive medium then no rotation of the plane of polarization will be observed.

When a linearly polarized or plane polarized beam passes through an optically active medium, its two circularly polarized components show different refractive indices (. the interaction of two components with the enantiomers i.e. optically active medium will be different). The difference in refractive indices arise because of the difference in the velocities of two components (i.e. rcp and lcp). The two components of linearly polarized light are slowed down relative to their equal velocities before the entrance into optical active medium. But the decrease in velocities of the two components will be to a different extents. As the two circularly polarized components travel with unequal velocities through the optically active medium, the two components are now not in phase and the resultant i.e. linear polarization ~~vec~~ vector gets rotated by an angle (α) to the original plane of polarisation.

It is well known that the value of optical rotation depends upon λ and by a change in λ, the α changes. The measurement of optical rotation as function of wavelength is known as optical rotatory dispersion. The medium (optical active) which interacts with two components of linearly polarized light differently is said to be circularly birefringent and the property of the medium to rotate the original plane of polarization is called circular birefringence.

Effect of circular birefringence: Let n_L and n_R be the refractive indices of left and right circularly polarised lights. When a linearly polarised light (lp) passes through an optical active medium, its two circularly polarised (cp) components shows different refractive indices ($n_L \neq n_R$). If n_L is greater than n_R, the RCP component of an linearly polarized wave travels faster than the LCP one in the chiral medium. The resultant electric vector of the RCP and LCP components no longer oscillate in original plane and oscillate in a new plane which is inclined at an angle α to the original plane.

$$\alpha = \frac{180}{\lambda}[n_L - n_R]$$

$$\text{Specific rotation } [\alpha]_\lambda^T = \frac{100\,\alpha}{lc}$$

$$[\phi]_\lambda^T = \frac{[\alpha]_\lambda^T \times M}{100}$$ Where M is molecular weight

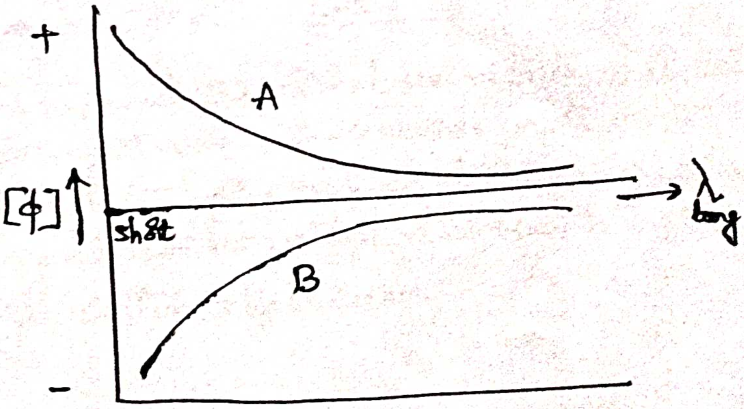
and $[\phi]_\lambda^T$ is molecular rotation.

From the above equation, it can be concluded that, if ~~the~~ RCP components travels faster than the medium is dextrorotatory (α is +ve). If LCP component travels faster, the medium is levorotatory.

A plot of angle of rotation (or $n_L - n_R$) versus wavelength (or frequency) gives an optical rotatory dispersion curve. There are two principal types of ORD curves

(i) Simple ORD curves.
(ii) Anomalous ORD curves.

(i) Simple ORD curves: If measurements of rotation is restricted to wavelengths away from λmax region then the ORD curves may either be plain or normal dispersion curves. The curve A and B show a steady decrease and increase in optical rotation with decrease of wavelength. The curve A is referred to as the plain positive dispersion curve, because the molecular rotation increases in the positive direction on going to shorter wavelengths.

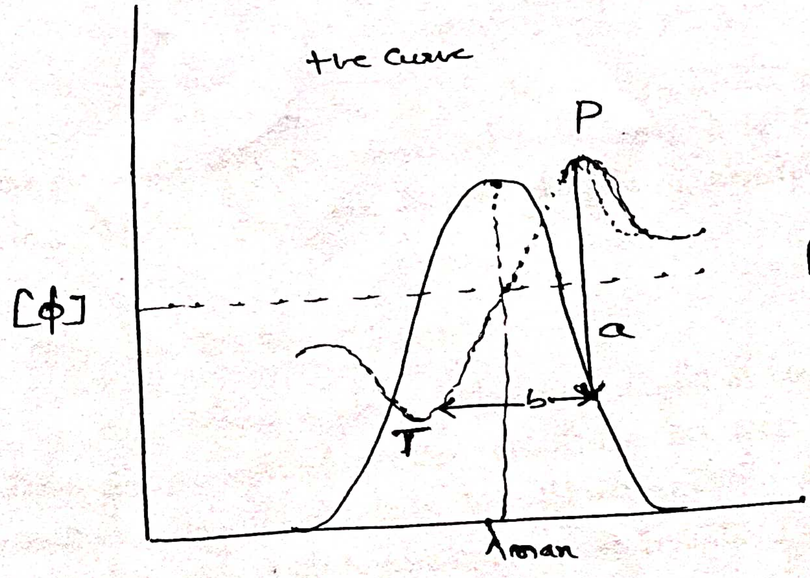


The curve B is referred to as a plain negative dispersion curve. These curves may & may not cross zero rotation line and these curves are smooth curves without any inflection.

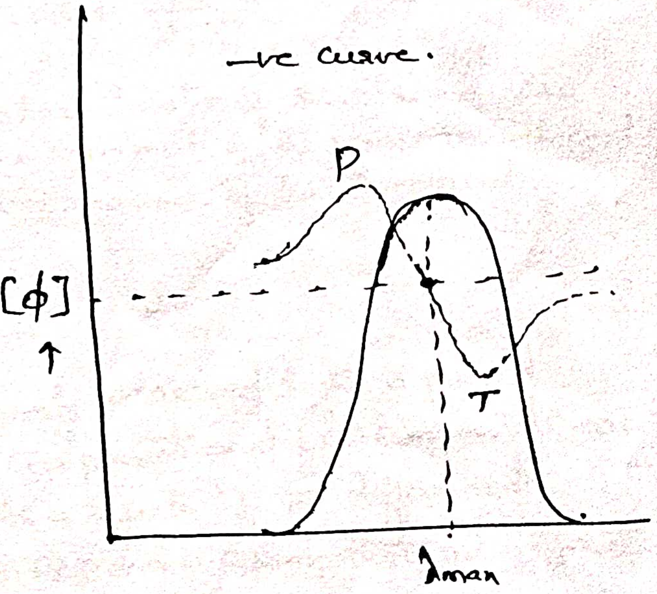
(ii) Anomalous ORD curves: If measurements of rotation is made in the region of λman then anomalous ORD curves will result. The anomalous ORD curve contains both the peak and trough. In these curves the trough & peak may appear at longer wavelengths. If peak appears at longer wavelength before trough then the ORD curve is positive ORD curve. In a negative ORD curve the trough appears at longer wavelengths. The term 'anomalous' is used because the curves do not obey the one term 'Drude equation'. Anomalous curves are of two types.

(A) Single cotton effect curves.
(b) multiple cotton effect curves.

Single cotton effect curves: Single cotton effect curve consist of a single peak and single trough.



Curve 'A'

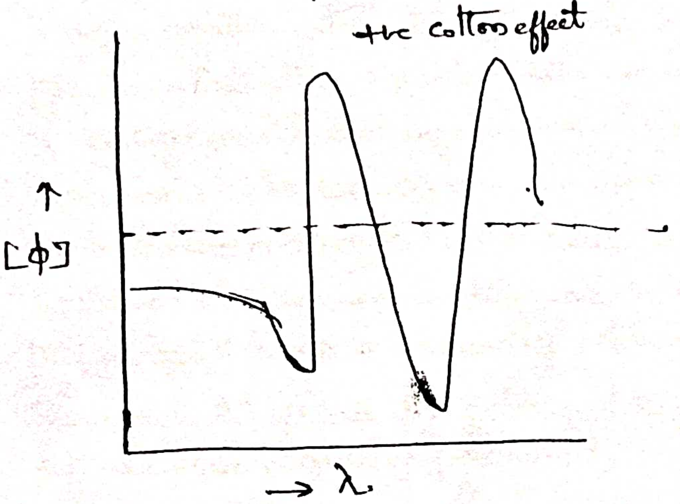


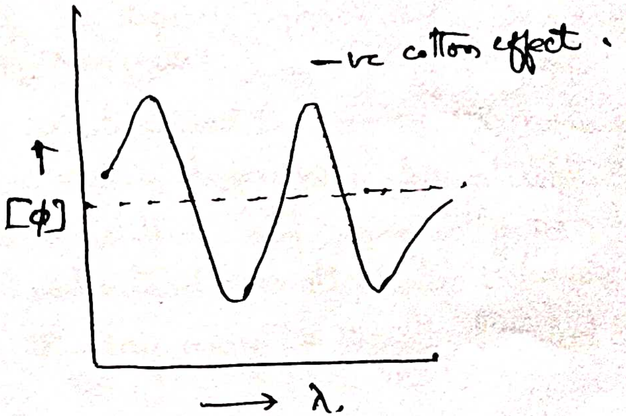
Curve B

The thick line curve in these diagrams represent the normal uv-visible absorption curve. The curve 'A' is a positive single cotton effect curve. The various points on the curve are designated as peak (P) and the trough (T). The vertical distance 'a' between the peak and trough is the amplitude and the horizontal distance 'b' is the breadth. The curve 'B' is negative single cotton effect curve.

b) Multiple Cotton effect curve:

A multiple cotton effect curve exhibits several peaks and troughs, with shoulders and inflection.





The mathematical expression used to describe the optical rotatory dispersion (ORD) is known as Drude equation.

$$[\phi] = \frac{K_1}{\lambda^2 - \lambda_0^2} + \frac{K_2}{\lambda^2 - \lambda_1^2} + \cdots + \frac{K_n}{\lambda^2 - \lambda_{n-1}^2}$$

Where $K_1, K_2, K_3 \ldots K_n$ are constants characteristic of the chromophores responsible for the observed rotations, λ is the wavelength of the measurements and $\lambda_0, \lambda_1 \ldots \lambda_{n-1}$ are the wavelengths of absorption maxima of the compound.

Circular Dichroism (CD):

When a plane polarised light & linearly polarised light is passed through an optical active medium the RCP component and LCP component are absorbed by the medium to different extent. As a result of the difference in absorption, the molar absorption coefficients for RCP and LCP component are different. i.e. $\epsilon_L \neq \epsilon_R$.

The measurement of unequal absorption of right and left circularly polarised components of a beam of linearly polarised light is known as Circular dichroism (CD). The difference in the molar extinction co-efficients of the RCP and LCP rays ($\Delta\epsilon$) is called differential dichroic absorption.

$$\Delta\epsilon = \epsilon_L - \epsilon_R \neq 0.$$

Upon emerging from the optically active medium, the two circularly polarized components not only are ~~outp~~ out-of-phase but are of unequal amplitude, i.e. the components are absorbed to different extents. If LCP component is absorbed to a ~~go~~ greater extent then $\epsilon_L > \epsilon_R$ and if RCP component is absorbed to a greater extent then $\epsilon_R > \epsilon_L$. The value of $\Delta\epsilon$ depends upon λ and a change in λ brings about a change in $\Delta\epsilon$. A plot of $\Delta\epsilon$ versus λ is nothing but the circular dichroism curve. In case of circular ~~Diod~~ Dichroism, the measurement of absorption is possible in the λ_{max} region and a difference in the absorption of LCP and RCP causes a difference in their amplitudes and consequently no more the emergent beam is circularly polarized, ~~and~~ instead it is elliptically polarised. Similar to the circularly polarized ray, this ray may be right handed or left-handed elliptically polarised.

∴ The specific ellipticity in terms of molar extinction co-efficient may be expressed as

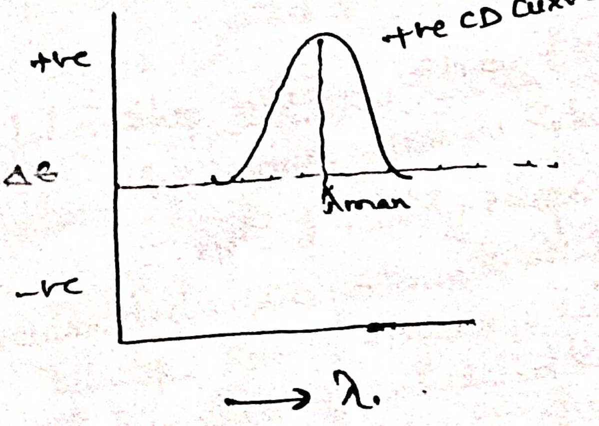
$$[\psi]^T_\lambda \text{ (in degrees)} = \frac{1800 \times 2.303 \times C \times 1000}{4 \times C \times \pi \times M} (\epsilon_L - \epsilon_R)$$

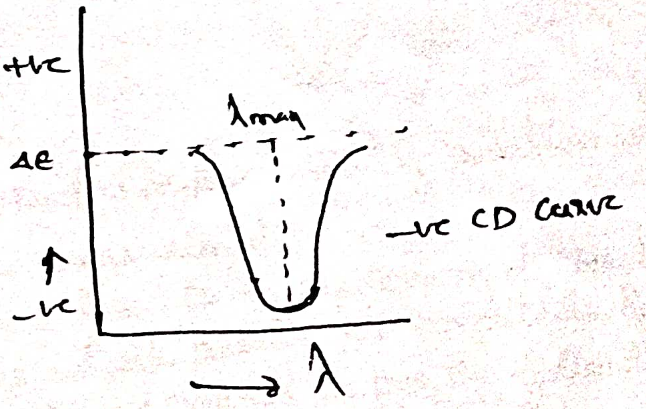
Consequently, the molar ~~ellipsity~~ ellipticity $[\theta]^T_\lambda$ can be expressed as follows

$$[\theta]^T_\lambda = \frac{1800 \times 2.303 \times C \times 1000 \times M}{4 \times C \times \pi \times M \times 100} (\epsilon_L - \epsilon_R)$$

$$\approx 3300 \times \Delta\epsilon$$

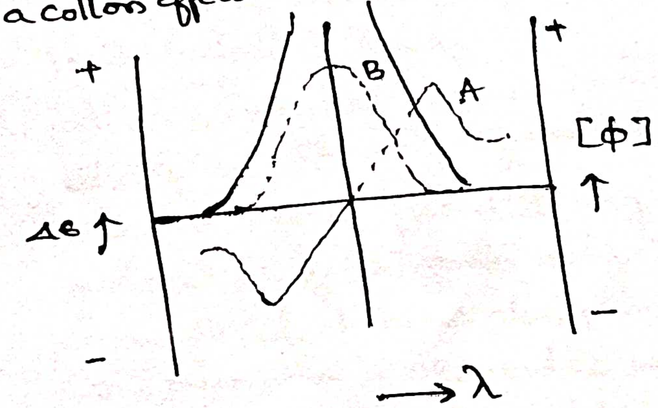
The circular dichroism curves are simple curve like Gaussian distribution curves.



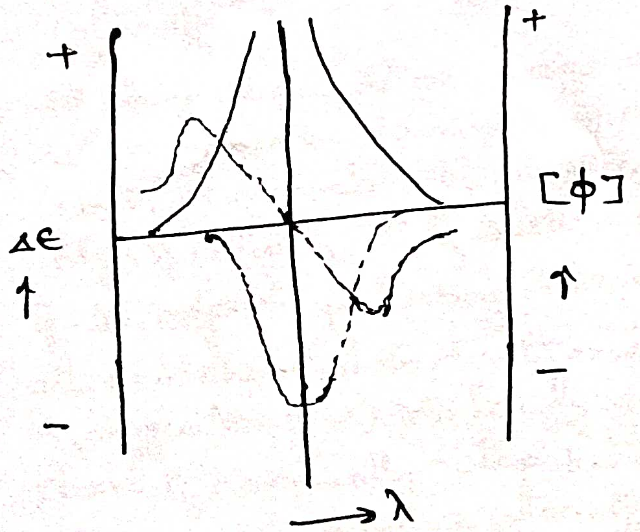


Cotton effect:

The combination of circular birefringence and circular dichroism gives rise to another important chiroptical phenomenon, namely the cotton effect. These ORD, CD and cotton effect phenomena are useful for assigning the absolute configuration and conformation of molecules. The ORD curve consisting of a peak and trough is known as anomalous or a cotton effect curve and is said to exhibit a cotton effect.



The cotton effect can be either positive or negative. The curve A represents ORD curve and is positive curve. The curve B is CD curve and is also positive. Hence, the cotton effect is also known as positive cotton effect.



The curve A is negative ORD curve and curve B is negative CD curve. Hence this effect is negative cotton effect.

Basing on the sign of cotton effect curve it is possible to assign the configuration and conformation of molecules.

Relationship between ORD and CD:

The Kronig-Kramers Relations:

The optical rotatory dispersion involves measurement of rotation whereas circular dichroism pertains to absorption measurement.

The Kronig-Kramers relations lead to an expression, derived from $n \rightarrow \pi^*$ transition of saturated ketones, which relate the amplitude of an ORD cotton effect to $\Delta\epsilon$ of the corresponding CD peak as per the following equation.

$$\alpha = 40.28\,\Delta\epsilon = (1.22\times10^{-2})[\theta]$$

Similarities and differences between ORD & CD:

The following are the similarities and differences between ORD and CD.

1. The ORD and CD spectrums are possible for chiral compounds and not possible for achiral compounds or racemic mixtures.

2. The measurement of rotation is involved in ORD and rotations can be measured over all wavelengths. The absorptions in CD i.e., the differential absorption of left and right handed circularly polarized radiation, is possible in the vicinity of λ_{max}.

3. A CD curve has close similarities in appearence with the ordinary (UV-vis) absorption. The only difference is CD curve can be either positive or negative. The CD curve is plotted taking $\Delta\epsilon$ (difference in molar absorptivity) or molar ellipticity $[\theta]$ along Y axis and λ along x-axis. The CD curve for each electronic absorption represents a positive or negative cotton effect. The phenomena of ORD and CD were first ~~observed~~ observed by french physicist Aim'e' cotton and hence the combined phenomenon is known as Cotton effect.

4. For many compounds ORD curves are plain curves. However for a compound with a symmetric chromophore eg. C=O group and with an adjacent asymmetric centre, an anomalous ORD curve called a coton effect curve is obtained. The sign of cotton effect of such a chromophore is determined by the chirality of the adjacent perturbing envirorment of the chromophore. The carbonyl group acts as a chromophore due to excitation of an electron in a non-bonding orbital n (oxygen lone pair) into low lying antibonding orbital (π bond). Thus the ORD curve of an optically active ketone in the region of $n \rightarrow \pi^*$ transition band (~290nm) will produce cotton effect.

5. The cotton effect could be either +ve or -ve.

6. At a given wavelength, if CD cotton effect curve is possible for a compound then there also exists a corresponding ORD cotton effect.

7. ORD spectra are dispersive whereas CD spectra are absorptive.

8. In ORD the circular polarised light used is not converted to elliptical light whereas in CD the circular polarized light used is converted to elliptical light.

In ORD, graphs are obtained by plotting specific rotation against wavelength where as in CD, the graphs are obtained by plotting molar ellipticity or $\Delta \epsilon$ against wavelength.

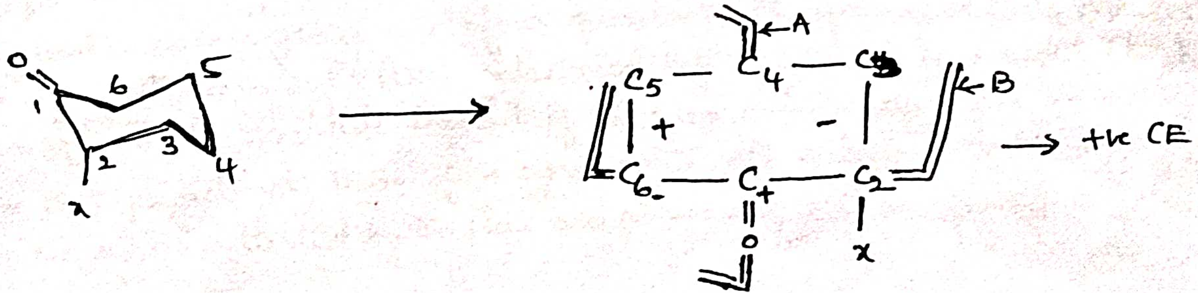
xial Halo Ketone Rule:

α-halocyclohexanone exist primarily in an axial conformation in contrast to other α-substituted cyclohexanones. The other substituents at α-position of (in axial conf) cyclohexanone bring about larger (stronger) dipole-dipole interactions, where as a halogen in axial conformation at α position cause lesser dipole-dipole interactions. Any substituent at α-position of cyclohexanone, in axial conformations, give rise to relatively larger rotations.

The axial haloketone rule is applicable to cyclohexanones containing an axial halogen (Cl, Br & I but not F) next to the keto group.

[Rule is not applicable to fluorine, because it has less polarizability when compared with hydrogen. Other halogens Cl, Br & I have higher polarizabilities than hydrogen]

Axial halo ketone rule is regarded as a precursor to the more generalised octant rule. The rule states that the introduction of an equatorial halogen in either α-position does not alter the sign of the cotton effect of the halogen-free ketone, ~~whereas~~ whereas the introduction of an axial halogen (Cl & Br) into the α-position may alter the sign of the cotton effect of the parent ketone.



The halogen at C_2 carbon in axial position causes +ve cotton effect, whereas the halogen at C_6-carbon (left) causes negative cotton effect. The axial halogen to the right will be in a (+) sector and hence cotton effect is +ve and axial halogen to the left will be in a (-ve) sector and hence cotton effect is -ve.

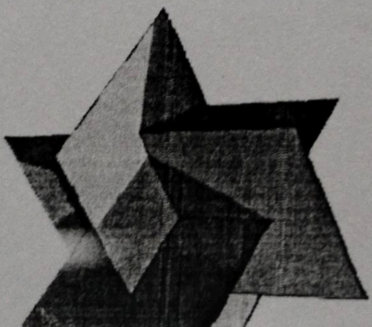
The ~~oct~~ octant rule:

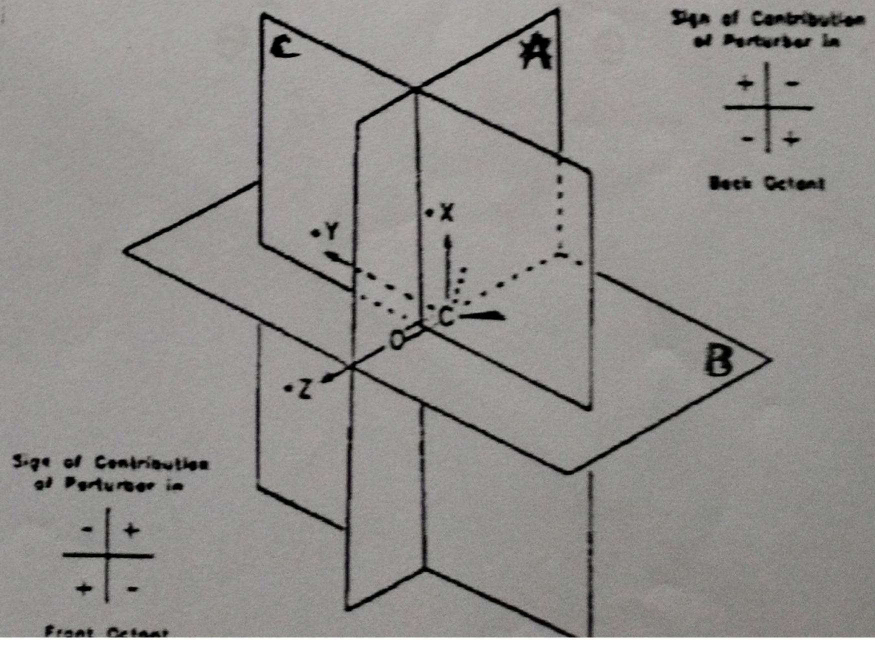
The octant rule was first formulated by Moffitt et.al for correlation of the sign of the cotton effect of chiral cyclohexanone derivatives with their absolute configuration. This octant-rule is used to predict the sign of the cotton effect in ORD and CD curves from a knowledge of the spatial arrangement (axial & equatorial) of the substituents around the carbonyl group. The rule has been used to predict the absolute configuration of compounds of unknown stereostructure.

The method of application of octant rule can be discussed as follows.

In a cyclohexanone, the space around the carbonyl group is divided into eight sectors (octants) about x, y and z axes with the help of three mutually perpendicular planes A, B and C.

The vertical plane A is assumed to pass through the carbonyl oxygen and carbons 1 and 4 (ie. it bisects cyclohexanone chair). Plane B is assumed perpendicular to plane A and includes C=O moiety and the two attached carbons C_2 and C_6. The plane C is assumed perpendicular to both the planes A and B and it intersects the carbon-oxygen double bond at the midpoint. The two planes A and B, now divide the space around carbonyl group into four quadrants. The four quadrants are designated as Upper left (UL), Upper right (UR), ~~lolo~~ lower left (LL) and lower right (LR). These four quadrants constitute the set of the rear octants (away from the observer). The groups that project into these four quadrants will contribute to the sign of the dispersion curve, as indicated by the plus and minus signs in the figure.





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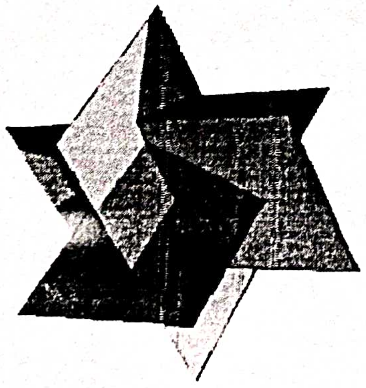

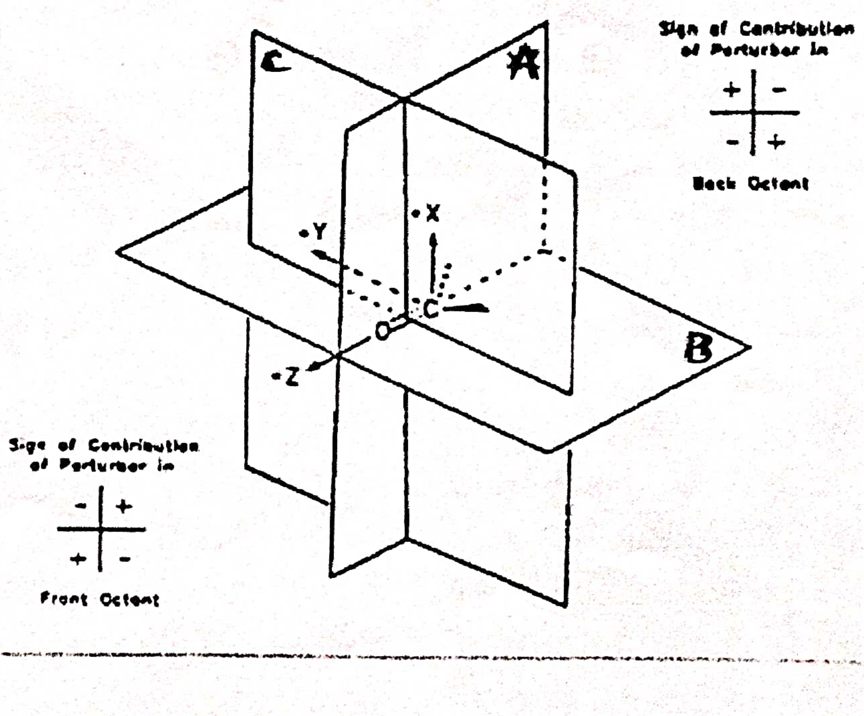

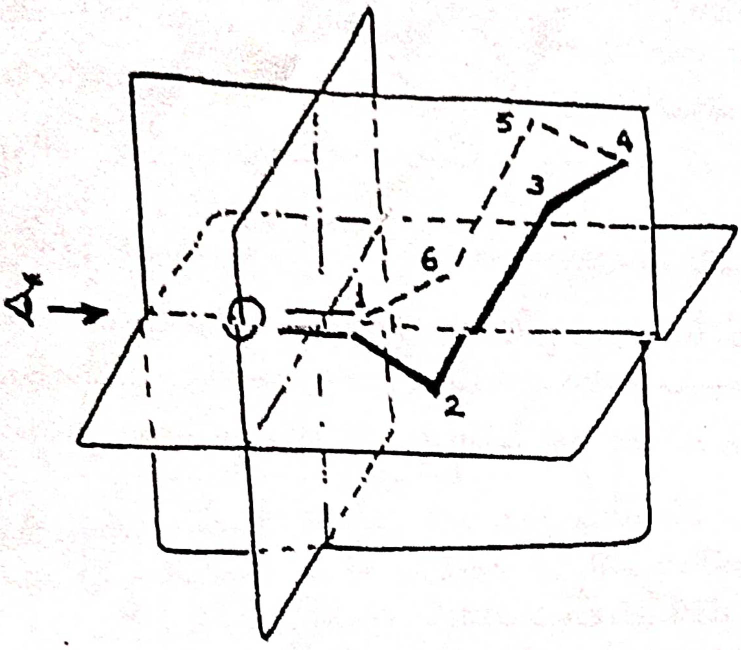
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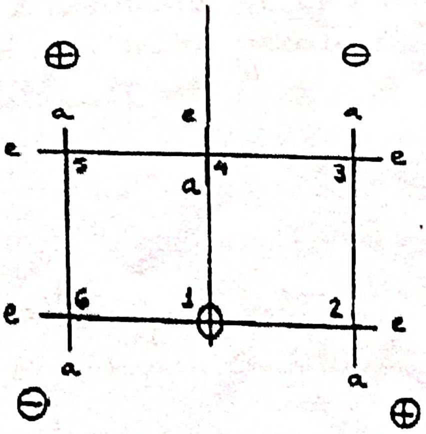
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In addition to the above mentioned four rear octants, there are four front octants. These front octants are ~~to~~ mirror images of the former. Thus, the substituents lying in the front ~~quadrants opposite~~ quadrants contribute ~~positively~~ oppositely i.e., their contribution to the sign of the cotton effect is exactly opposite to those shown in the figure above.

In majority of substituted cyclohexanones, the substituents will appear only in the four rear quadrants and very rarely, a part of some molecules appear in the front quadrants. Hence in simple cyclohexanones, plane 'C' may be ignored and only the four rear quadrants defined by planes A and B need to be considered.

According to octant rule, the substituents lying on the coordinate planes make negligible (ignorable) contribution to the cotton effect. Thus, the ~~sed~~ equatorial substituents at C-2 and C-6 make little contribution as these lie on the plane (B). Similarly, substituents at C-4, both axial and equatorial make no contribution since they lie on plane (A).

Axial substituents at C-2 and all substituents at C5 make a positive
Axial substituents at C-2 and all substituents at C-3 make a negative contribution. Axial substituents at C-6 and all substituents at C-6 make greater contribution to contribution. The axial substituents at C-2 and C-6 make greater contribution to the cotton effect than the far removed substituents at C-3 and C-5, from carbonyl group.

Applications:

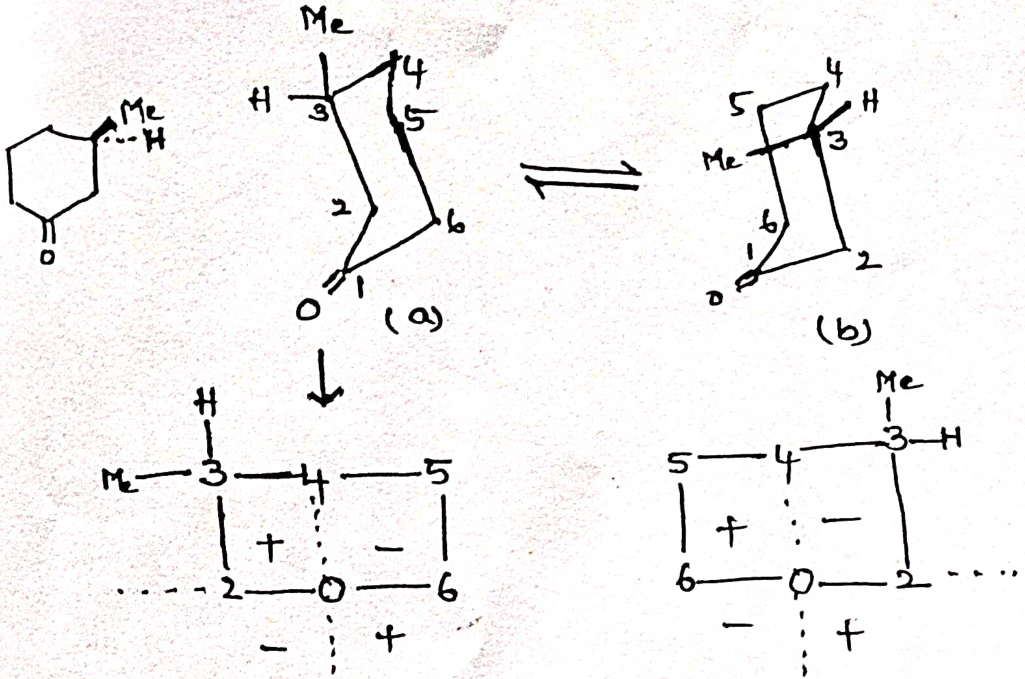
(1) octant rule is useful to determine the position of the ketogroup and the configuration of ring system in ketosteroids of unknown constitution.

(2) The absolute configuration of complex molecules can ~~also~~ be assigned using octant rule.

3) Octant rule is also helpful in knowing the stereochemistry of Amino acids.

4) Determination of Preferred conformation:

3-methylcyclohexanone has two possible conformations. The preferred conformation can be determined by an application of the octant rule



+ve cotton effect

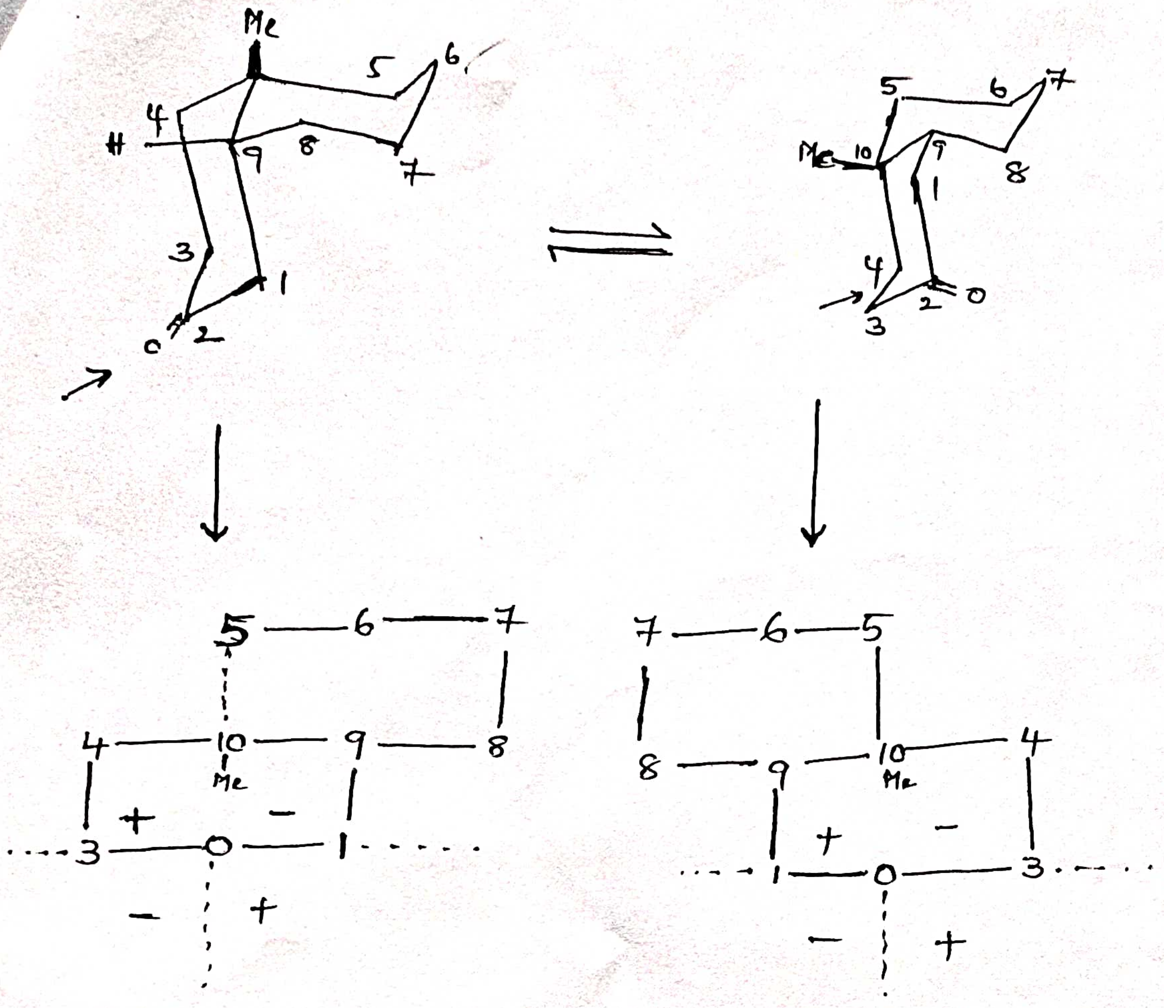
−ve cotton effect.

According to the octant rule, the equatorial conformer (a) should exhibit a positive cotton effect (3-Me is in the UL octant) while the axial conformer (b) would exhibit a negative cotton effect (3-Me is in the UR octant). Actually, the molecule shows a positive cotton effect and hence prefared conformation is equatorial conformation.

(5). Determination of conformation of (+)-cis-10-methyl-2-decalone:-

Two conformations (I & II) are possible for (+)-cis-10-methyl-2-decalone which exhibit different contributions to the cotton effect.

The application of the cotton effect reveals that the conformation I should give the negative cotton effect (ring B being in the negative sector), while the structure II displays a positive cotton effect (ring B being in the positive ~~sed~~ sector). Actually, it gives a negative cotton effect and so has the conformation-I.



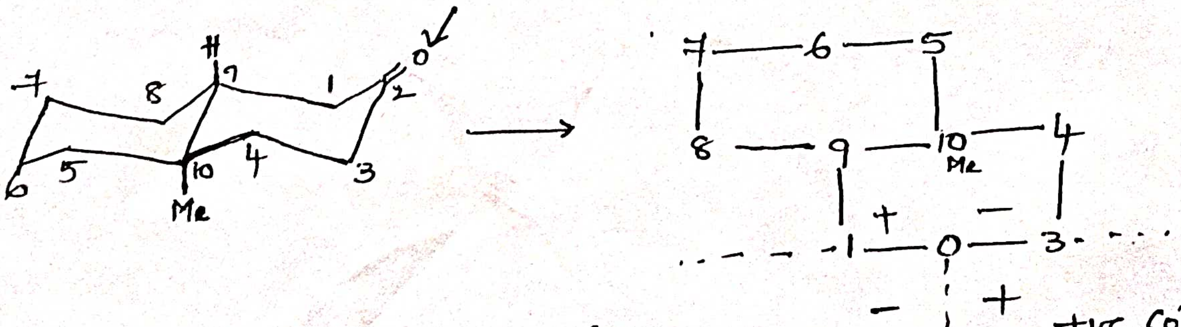
−ve cotton effect

+ve cotton effect.

Conformation of (+) − cis − 10 − methyl − 2 − decalone

). **Determination of Configuration:**

Trans − 10 − methyl − 2 − decalone exists in a rigid conformation as shown in figure. The absolute configuration of (+) enantiomer shows a +ve cotton effect, in consistence with the octant rule (ring B in the projection lies in the positive effect).



+ve Cotton effect.

configuration of trans − 10 − methyl − 2 − decalone.