STEREOCHEMISTRY OF CHLORINE ADDITION TO TRANS-Δ^2-OCTALIN

Thesis by

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ABSTRACT

The chlorination of trans-Δ^2-octalin has been shown to produce diaxial-dichlorides and diequatorial-dichlorides in the ratio of two to one. The results are explained in terms of a mechanism involving a cyclic chloronium ion.

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Perhaps one of the oldest fields of chemistry is the study of the reactions of olefins. It might be argued by analogy with the E_2 elimination mechanism that the electrophilic addition to a cyclic olefin would require a trans-diaxial introduction of the new groups. However other mechanisms suggest less stereospecific results. In order to clarify the understanding of the mechanism, the determination of the stereochemistry of the products of the chlorination of trans-Δ^2-octalin was undertaken.

The kinetics of halogen addition to olefins have been found to be complex. The reaction which is first order in the halide in polar solvents may be shifted to second order in the halide by a shift to a less polar solvent. In the presence of nucleophiles other product besides the 1,2-dihalides are produced. In nonpolar solvents the kinetics become extremely complex and are not well understood.[1]

It has also been observed that rearrangement may accompany electrophilic additions. The addition of hydrogen chloride to isopropylethylene has been shown to give equal amounts of secondary isoamyl chloride and tert-amyl chloride.[2] Addition of hydrogen chloride to tert- butylethylene gave 60-65% rearranged product.[3]

Hammond and co-workers have found in a stereochemical study of the addition of hydrogen halides to olefins that the

trans product predominated. They have shown that the addition of hydrogen bromide to 1,2-dimethylcyclohexene[4] and of hydrogen chloride to 1,2-dimethylcyclopentene[5] in pentane gave predominantly the trans addition product. A trans out-of-the-plane attack either through a pi-complex or completely concerted was proposed to account for these results, figure I.

A further study of the stereochemistry of hydrogen halide addition to olefins was undertaken by Dewar and Fahey. They have shown that the addition of deuterium chloride to acenaphthylene and the addition of deuterium bromide to acenaphthylene,[6] indene,[7] or either cis- or trans-1-phenylpropene[8] under polar conditions takes place predominantly cis. They proposed that this evidence could best be accounted for by a mechanism involving a classical carbonium ion in the rate determining step as an ion pair with a halide ion, figure II. Step 2 is rate determining and leads to the ion pair which may collapse directly to give cis addition or isomerize before collapse to give trans addition. The trans products produced from the additions to 1,2-dimethylcyclohexene is accounted for by steric effects in the 1,2-dimethylcyclohexane system. In order for the ion pair to collapse directly to give cis addition the two methyl groups must pass through an eclipsed configuration, figure III.

The addition of halogens to olefins might be expected to follow a mechanism similar to that of the addition of hydrogen halides. In order to test this hypothesis and obtain information

Figure I

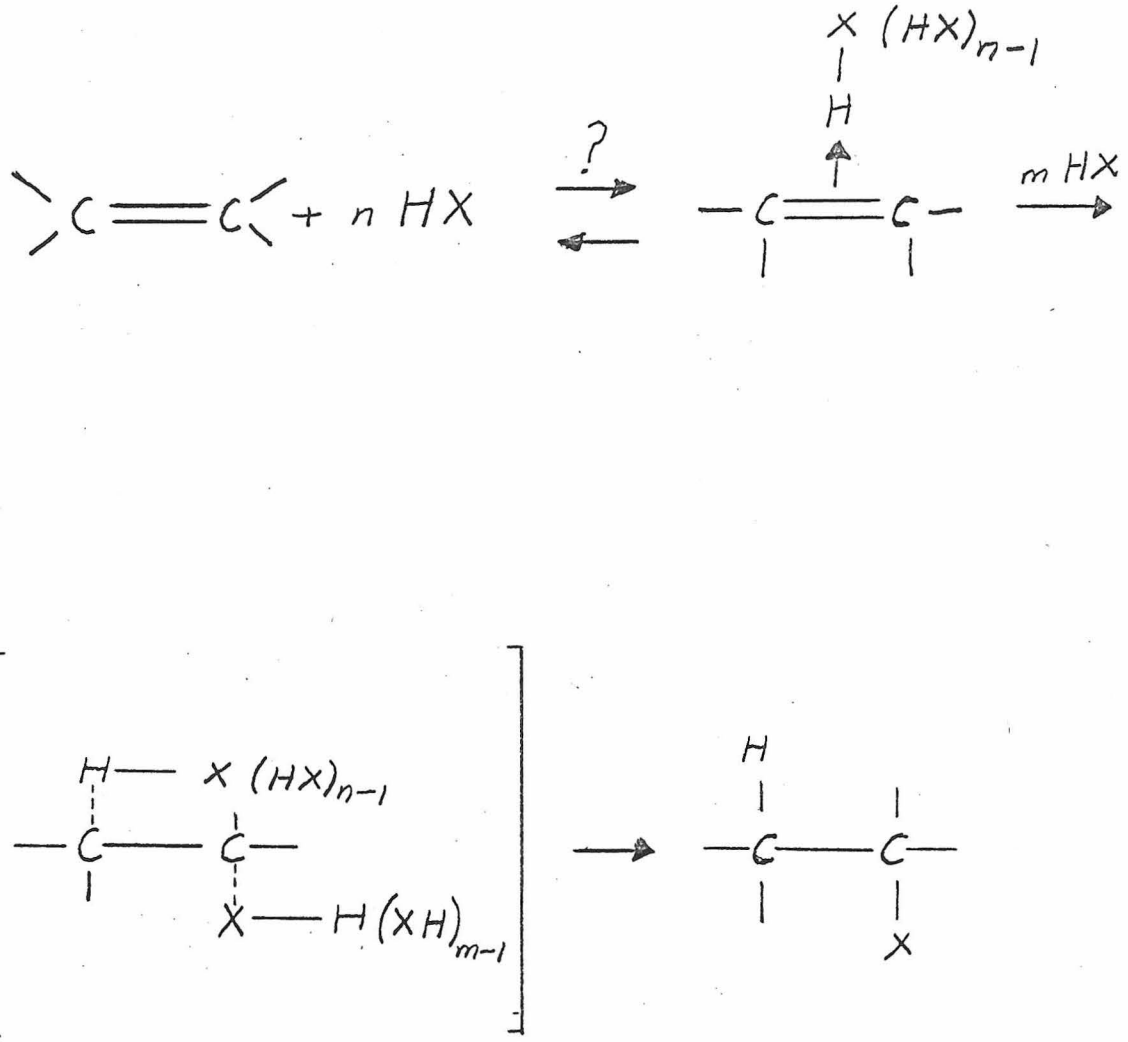
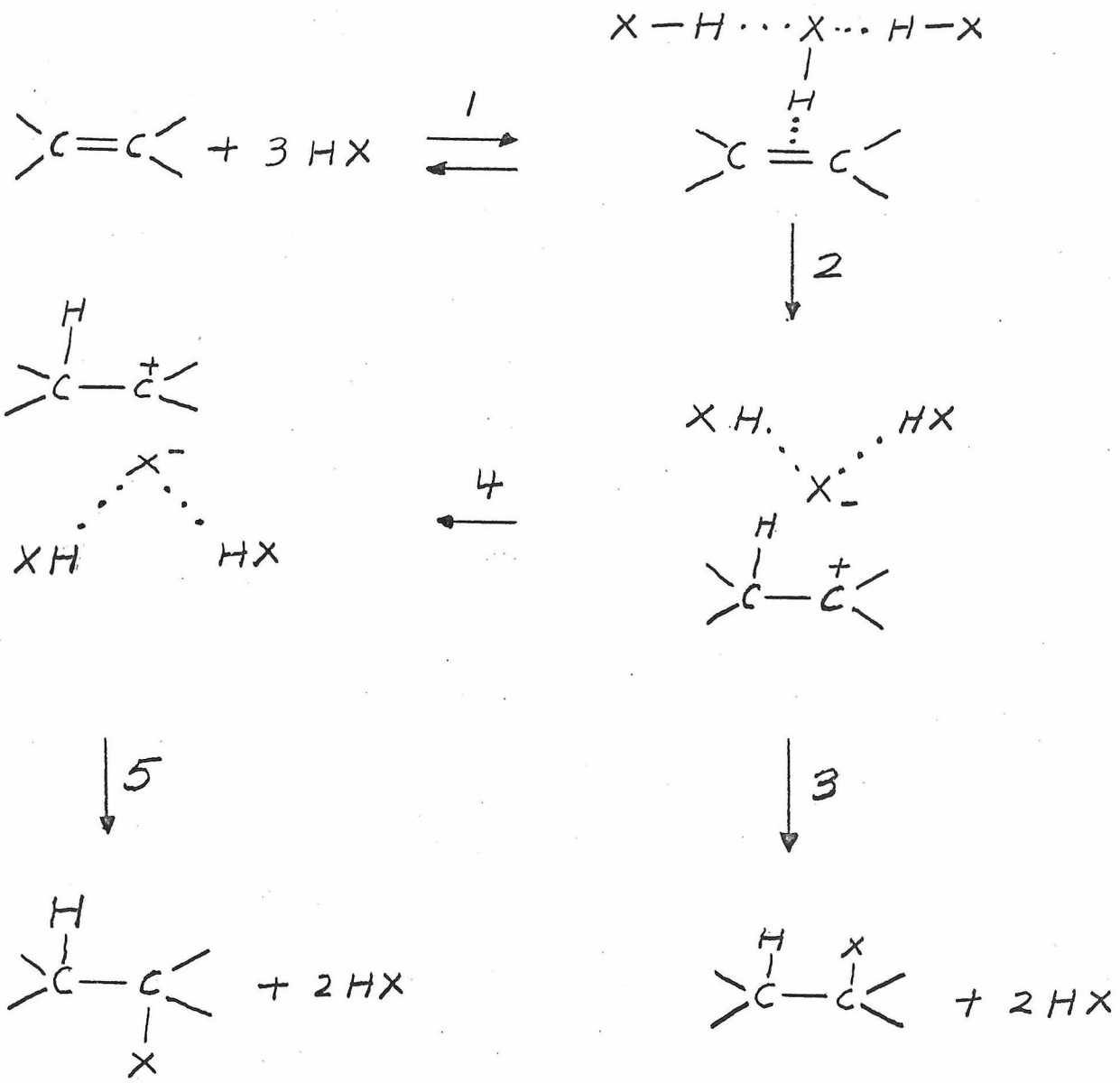


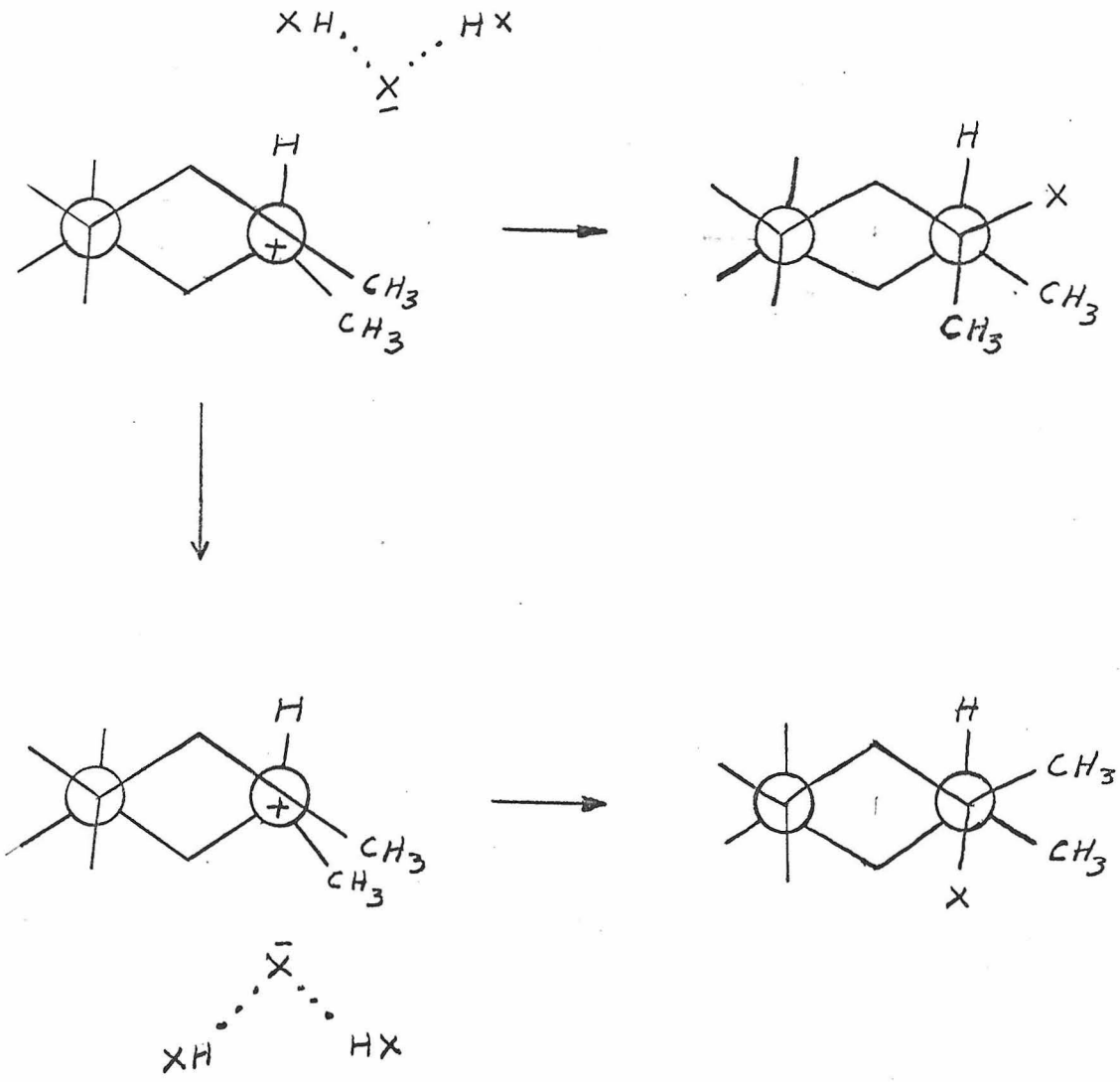
Figure II



trans adduct

cis adduct

Figure III

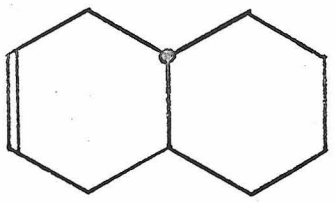


about the stereochemistry of the addition of halogens to olefins, the addition of chlorine to trans-Δ^2-octalin was undertaken.

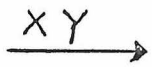
Trans-Δ^2-octalin is nearly an ideal substrate for a stereochemical study of electrophilic additions. Once the addition has been completed the stereochemistry can not change due to rotation about the newly produced carbon-carbon single bond. The trans-decalin system contains two rigid six membered rings in such an environment that neither ring can flip as is possible in a simple cyclohexane system. It is also improbable that the mechanism of the addition to trans-Δ^2-octalin proceeds through a boat intermediate. There is an 11 Kcal energy barrier between the chair and boat conformation of cyclohexane with the energy of the boat conformation about 4 Kcal higher than the energy of the chair conformation.[9] The four isomeric products, a trans-diaxial (2), a trans-diequatorial (3), and two cis isomers (4) and (5), which may be produced from the addition of XY to trans-Δ^2-octalin are shown in figure IV.

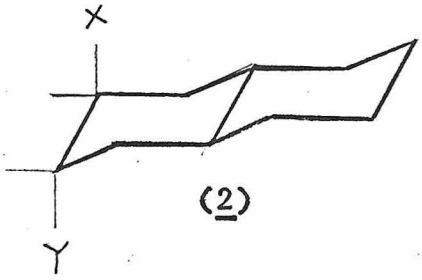
Previous work indicates that the two trans isomers should be produced in the chlorination of trans-Δ^2-octalin. Barton[10] has found that chlorination of cholest-2-ene (6) in carbon tetrachloride gave two products, (diaxial) 2β:3α-dichlorocholestane (7) and (diequatorial) 2α:3β-dichlorocholestane (8). The diaxial isomer predominated over the diequatorial isomer in the ratio of 2.6:1. Garwood[11] has found that the chlorination of

Figure IV

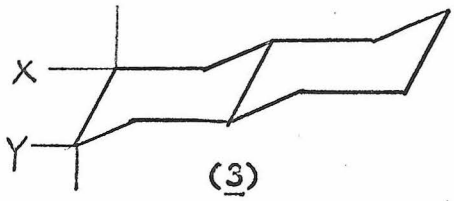


(1)





(2)



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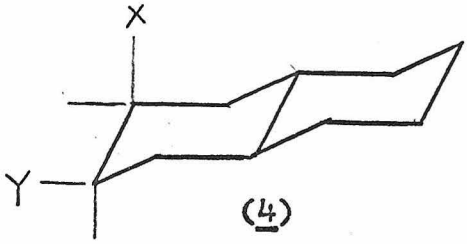

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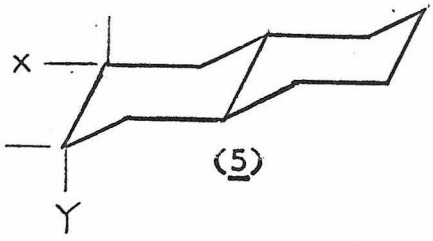
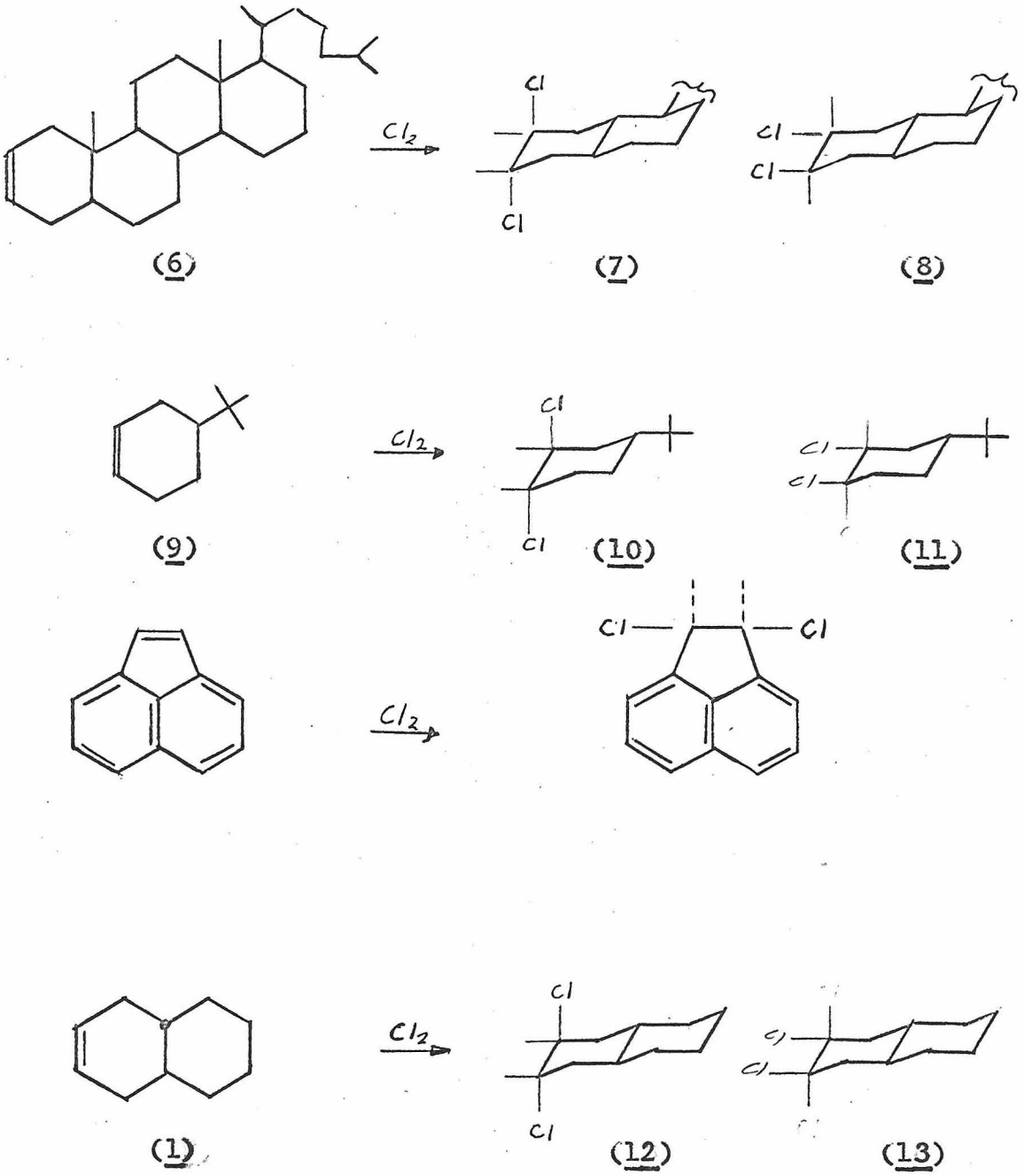


(5)

Figure V



4-t-butylcyclohenene (9) in various solvents also produces two isomers, trans-diaxial-1,2-dichloro-4-t-butylcyclohexane (10) and trans-diequatorial-1,2-dichloro-4-t-butylcyclohexane (11). The diaxial isomer again predominated in most solvents and ratios are tabulated in Table I.

However cis addition of chlorine to olefins has also been reported. Cristol has found that chlorine adds to acenaphthylene in carbon tetrachloride, benzene, or petroleum ether by a polar mechanism to give the cis addition product in about 20% yield.[12] The mechanism proposed by Dewar will acount for this product.

Trans-Δ^2-octalin was chlorinated at ice bath temperatures in a number of solvents with the exclusion of light in the presence of anthracene. Light was excluded and anthracene added to prevent addition by a free radical mechanism.[11] Two isomers, trans-diaxial-2,3-dichloro-trans-decalin (12) and trans-diequatorial-2,3-dichloro-trans-decalin (13) were produced with an over all yield of 72%.

The isomers were detected by vapor phase chromatography. Two separate peaks were observed using an apieson L column with helium as the carrier gas. The ratio of the isomers was determined by the area of the peaks which in turn was determined by the peak height times the peak width at half height. The results for various solvents are summarized in Table I. The error in these results should not exceed 5% due to the vapor phase chromatography analysis.

Table I

Addition of chlorine to	Solvent	Addition products		Reference
Acenaphthylene	CCl_4	cis		12
	benzene	cis		
	pet. ether	cis		
		Diaxial 2β:3α-	Diequatorial* 2α:3β-	
Cholest-2-ene	CCl_4	72%	28%	10
		Diaxial	Diequatorial	
4-t-butyl-cyclohexene	pentane	74%	26%	11
	benzene	72	28	
	chlorobenzene	59	41	
	acetic acid	25-30	70-75	
Trans-Δ^2-octalin	pentane	67.5	32.5	
	CCl_4	66	34	
	$CHCl_3$	67	33	
	CH_2Cl_2	63	37	
	chlorobenzene	62	38	
	acetic acid	59	41	

* Yields adjusted to add up to 100%

Two other products were found on the vapor phase chromatograph with a retention time longer than either of the major products. These two products together comprise less than two precent of the total product, and no attempt was made to identify them. The remaining 26% of the starting material was not observed on the vapor phase chromatograph and may be due to errors in the determination of the yield.

The two major products were identified by their nuclear magnetic resonance spectra and their chemical properties. The nuclear magnetic resonance spectrum of the isomer with the short retention time exhibited a narrow doublet at 4.33 ppm relative to TMS corresponding to equatorial hydrogens (reported for equatorial hydrogen in chlorocyclohexane, 4.40 ppm[13]) and a broad peak in the 1-2 ppm region corresponding to the trans-decalin spectrum. The isomer with the long retention time exhibited a wide peak at 3.71 ppm corresponding to axial hydrogens (reported for axial hydrogen in chlorocyclohexane, 3.68 ppm[13]) and the broad trans-decalin peak.

A mixture of the two isomers was treated with zinc and acetic acid at steam bath temperatures for $4\frac{1}{2}$ hr. Periodic analysis of the reaction mixture on the vapor phase chromatograph showed the isomer with the short retention time dechlorinated to give trans-Δ^2-octalin. After all the isomer with the short retention time had been converted to trans-Δ^2-octalin the reaction was continued and no change in the relative amounts of the isomer with the long retention time and the trans-Δ^2-octalin was observed. The isomer with the short retention time was thus assigned the diaxial structure (12) and the isomer with the long retention time the diequatorial structure (13).

It was also shown that no isomerization occurred either during the vapor phase chromatography or under the reaction conditions. Samples of the pure isomers with the long and short retention times were collected from the vapor phase chromatography column outlet and rechromatographed. In each case only one peak resulted. Small amounts of the diaxial and the diequatorial-2,3-dichloro-trans-decalin were separately dissolved in pentane and treated as in the chlorination of trans-Δ^2-octalin. No isomerization resulted. Periodically during the chlorination reactions aliquots were taken from the reaction flask and chromatographed on the vapor phase chromatograph. In all cases the the ratio of the area of the isomer with the long retention time to the area of the isomer with the short retention remained constant throughout the reaction, and there was no indication of isomerization of the trans-Δ^2-octalin.

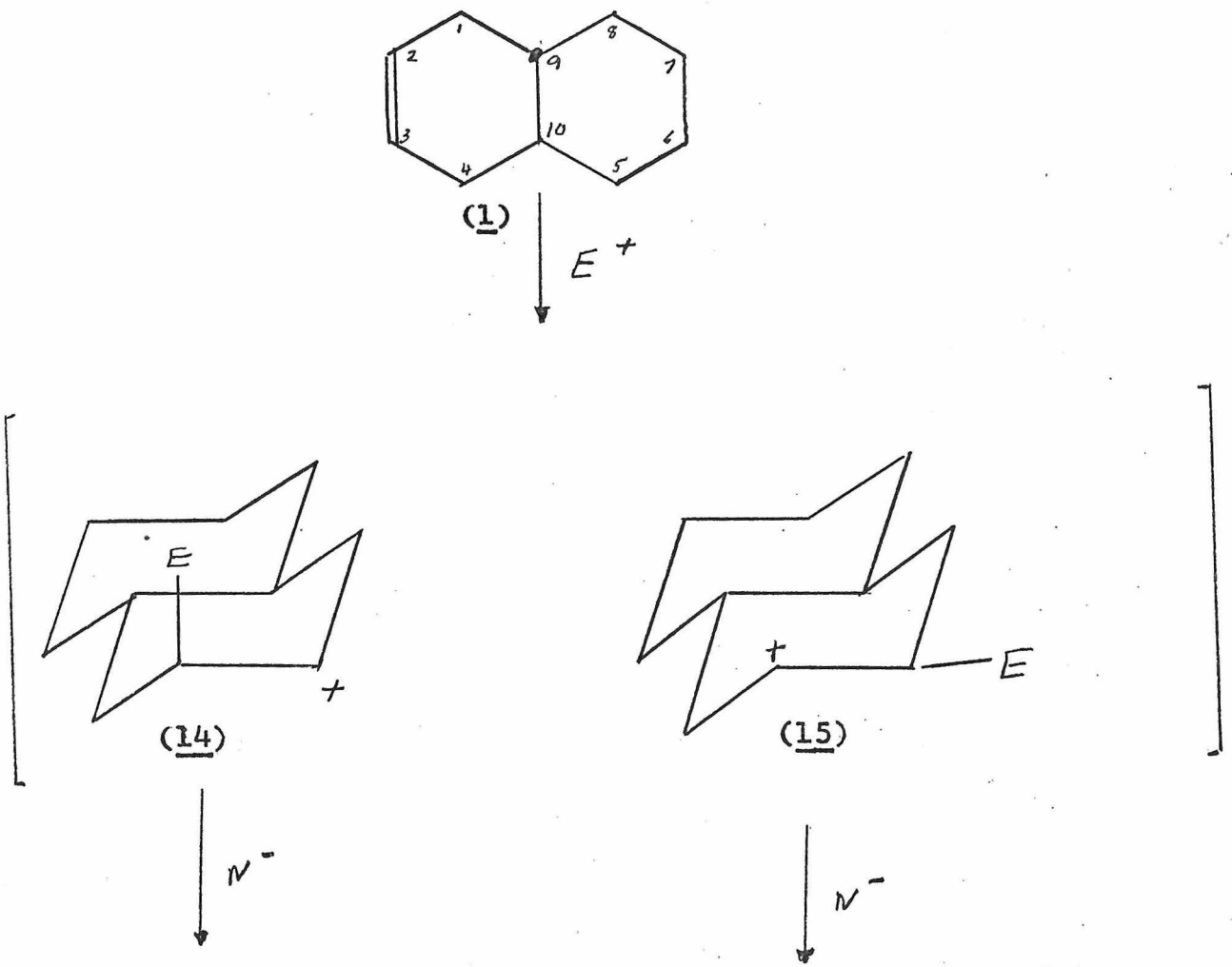
The two isomers were separated by chromatography over alumina and each was found to give only the expected retention time on the vapor phase chromatograph. The nuclear magnetic resonance spectrum of the separated isomers showed only equatorial hydrogens alpha to the chlorine for the isomer withthe short retention time and only axial hydrogens alpha to the chlorine for the isomer with the long retention time. If any cis product had formed it would have been detected by the analysis of the products on the vapor phase chromatograph unless it had the same retention time as one of the products. If it had the same retention time both axial and equatorial hydrogens alpha to the chlorine would have been

found in the nuclear magnetic resonance spectra of the separated isomers. Since only one type of hydrogen was found in each case, no cis addition product could have been formed.

Any mechanism proposed for this reaction must account for the formation of the two isomeric dichlorides and the formation of additional products in the presence of nucleophiles. Mechanisms involving a classical carbonium ion, a trans planar attack with the formation of a boat intermediate to produce diequatorial products, and a cyclic chloronium ion have been proposed and will be considered.

A mechanism involving a classical carbonium ion as an intermediate, figure VI, has been proposed, however the absence of a cis addition product is difficult to explain. An electrophile may attack either carbon of the double bond and produce carbonium ions with the electrophile in either the axial (14) or equatorial (15) position. The ratio of the amounts of the two carbonium ions produced ought to be related to their difference in free energy by $K = e^{-kT\Delta F}$ where K = equilibrium constant, k = Boltzmann's constant, T = temperature in degrees K, and ΔF = difference in free energy. The difference in free energy between an axial chlorine and an equatorial chlorine in chlorocyclohexane has been found to be between 0.3 and 0.5 kcal[9]. A similiar energy difference between the two carbonium ions leads to the conclusion that the carbonium ion with the chlorine atom in the equatorial position should predominate over the carbonium ion

Figure VI

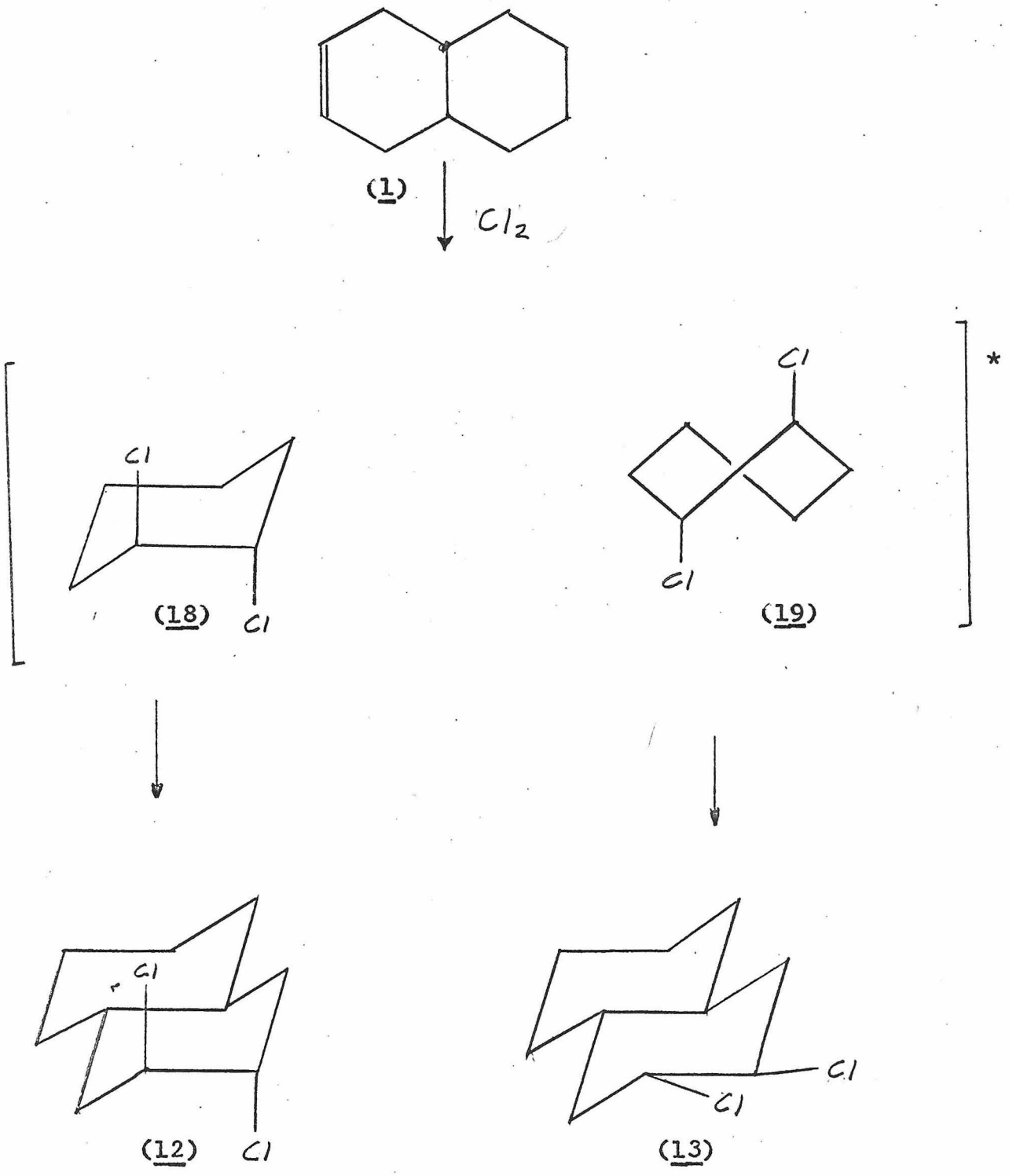


with a chlorine atom in the axial position by a factor on the order of two. Both ions may be attacked by a nucleophile at the least hindered, equatorial, position. Attack by a nucleophile on the carbonium ion with an electrophile in the equatorial position would lead to a diequatorial product (17), while attack by a nucleophile on the carbonium ion with an electrophile in the axial position would lead to the cis product (16). Since no cis product was formed in the chlorination of the trans-Δ^2-octalin, the mechanism can not involve a classical carbonium ion as an intermediate.

A mechanism requiring that in the transition state the entering groups, the electrophile and the nucleophile, must lie anti to each other, figure VII, must proceed through a boat conformation of the decalin system to produce the diequatorial product. If this is the case the energy difference between the transition state with the entering groups axial and the decalin in the chair conformation and the transition state with the entering groups axial and the decalin in the boat conformation must be only 0.4 kcal. The energy difference of 0.4 kcal is required to account for the observed ratio of 2 to 1 of trans diaxial to trans diequatorial product.

However, the energy difference between the chair and boat conformation of the transition states mustbe greater than 4.0 kcal. The energy difference between an axial and an equatorial chlorine in chlorocyclohexane is only 0.3-0.5 kcal.[9] Thus trans-diaxial-2,3-dichloro-trans-decalin (12) is only 1 kcal less stable

Figure VII



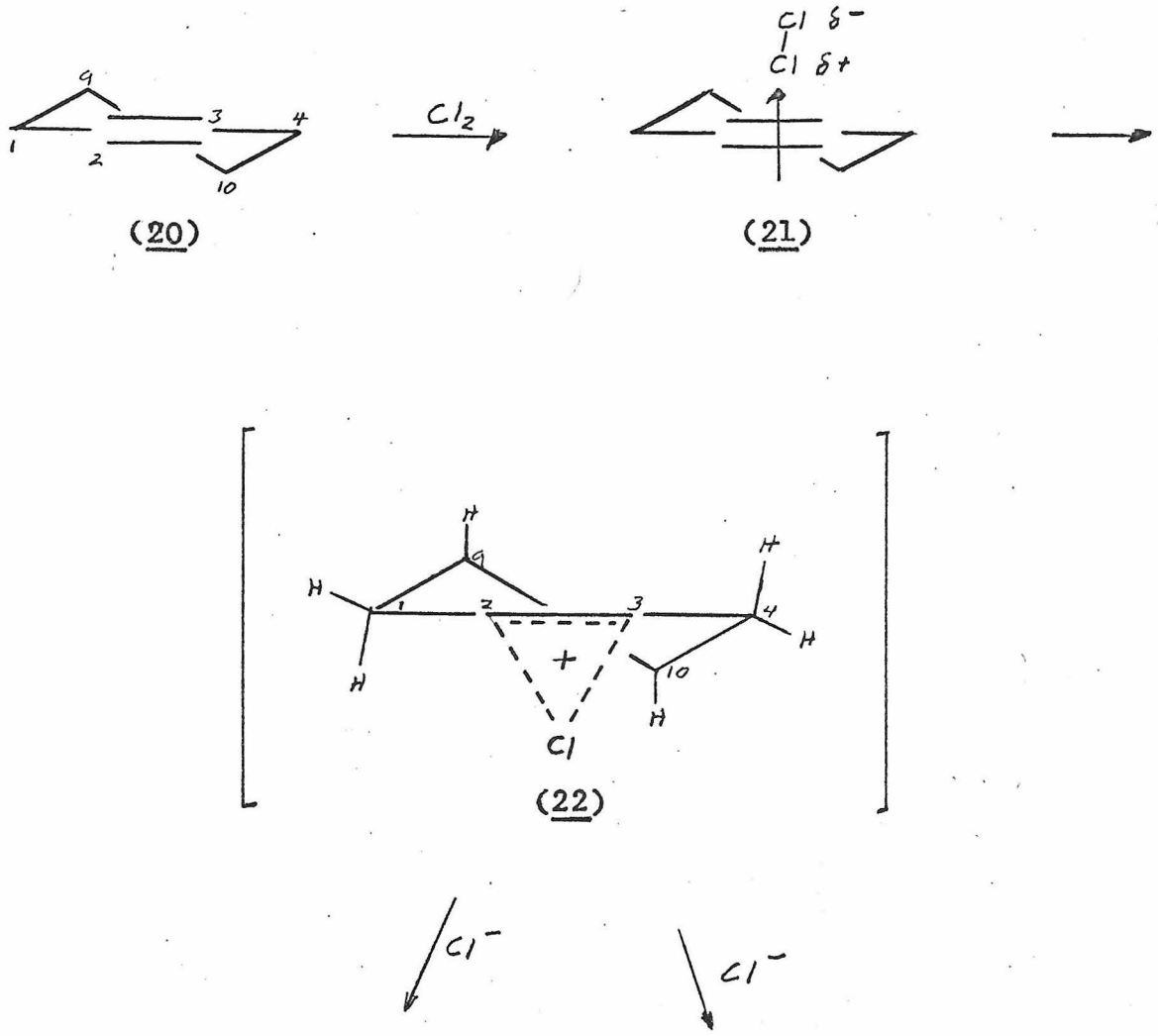
* The second ring of the decalin system was not drawn in the transition state to make the diagrams simpler.

than trans-diequatorial-2,3-dichloro-trans-decalin (13). The boat conformation of trans-diequatorial-2,3-dichloro-trans-decalin (19) must be greater than 5 kcal less stable than the chair conformation(13). The energy difference between the chair and boat conformations of cyclohexane have been found to be about 5 kcal.[9] This energy difference is due to the 1,4 flag-pole interaction and the eclipsed conformation of the 2- and 3- and the 4- and 5-carbons. These interactions may be reduced by the formation of a twist conformation, however the energy difference still remains at least 5 kcal between the chair and boat conformations. The interaction between a chlorine and a hydrogen in the 1,4 flag-pole positions of a boat conformation must be greater than the interaction between two hydrogens in the 1,4 flag-pole positions. The energy of an eclipsed chloroethane must also be higher than the energy of an eclipsed ethane. Thus the energy of the boat conformation must be at least 5 kcal higher than the energy of the chair conformation of trans-diequatorial-2,3-dichloro-trans-decalin and 4 kcal higher than the energy of the chair conformation of trans-diaxial-2,3-dichloro-trans-decalin.

A mechanism requiring the formation of a cyclic chloronium ion in the transition state, figure VIII, seems to account for the observed products. The cyclic chloronium ion (22) can be formed from a pi-complex.(21).

Formation of a pi-complex, in which the pi-electrons of the double bond are loosely complexed with the electrophile, has been demonstrated in the addition of iodine to cyclohexene. The iodine

Figure VIII



(12) (13)

To simplify the diagram the second ring in the decalin system is only drawn in the products.

solutions in cyclohexene are brown, while the iodine solutions in cyclohexane are violet.

The cyclic chloronium ion will be formed by overlap of the p-orbitals of the double bond with the orbitals of the chlorine atom. The chloronium ion as shown in (22) may be attacked by a nucleophile at either the 2- or the 3-carbon to give the trans-diaxial or the trans-diequatorial products respectively. Attack at the 3-carbon will be hindered by the steric effects of partial eclipsing with the pseudo-axial hydrogen on the 4-carbon. There will be no similar steric effect for attack on the 2-carbon since the nearest hydrogen on the 1-carbon is in the pseudo-equatorial position. There will be an opposite steric effect from the hydrogen on the 9-carbon, however it will be much smaller since the relative distances between it and the attacking group over the 2- or 3-carbon will be nearly the same. Thus the energy difference of 0.4 kcal needed between the transition state leading to the diaxial and the diequatorial isomer can be accounted for by steric interactions between the attacking group and the hydrogen on the alpha carbon.

This mechanism is consitent with the observed kinetics of the addition of chlorine to olefins. The reaction has been found to be first order in both olefin and chlorine when run in polar solvents. In non-polar solvents it has been found to remain first order in chlorine unlike the addition of bromine which becomes second order in non-polar solvents. The shift to second order in the case of bromine

is accounted for by the formation of a large tribromide ion which disperses the negative charge in non-polar solvents. Chlorine forms the trichloride ion only with difficulty and thus no shift to second order is observed.[14]

In summary electrophilic addition of chlorine to trans-Δ^2-octalin had been shown to produce bothtrans-diaxial and trans-diequatorial 2,3-dichloro-trans-decalin. The most probable mechanism to account for these products involves a cyclic chloronium ion which may be attacked to give either of the products.

EXPERIMENTAL

Trans-Δ^2-octalin:

Trans-Δ^2-octalin was prepared by the method of Johnson.[15]

Chlorination of trans-Δ^2-octalin:

a. in chloroform: Trans-Δ^2-octalin (1.0 g) was dissolved in chloroform (17 ml) and added to anthracene (0.1 g) in a 100 ml three necked round bottom flask fitted with serum cap, thermometer, magnetic stirrer, and gas inlet and outlet. The flask was wrapped in foil and immersed in an ice.bath. Chlorine was bubbled through the solution for 48 min, and aliquots were taken through the serum cap at intervals and chromatographed on a vapor phase chromatography apieson L column. The temperature was followed and found to range from 4-9°. The aliquots became increasingly yellow as the chlorine flowed through the solution but cleared rapidly upon reduction of the pressure with an aspirator. There was also an odor of hydrogen chloride when the flask was opened. The vapor phase chromatography analysis showed that the diaxial isomer predominated over the diequatorial isomer in the ratio of 2:1.

b. in pentane: Trans-Δ^2-octalin (1 g) was dissolved in redistilled pentane (10 ml) saturated with anthracene (approximately 0.05 g) and added to a three necked 100 ml round bottom flask fitted with a serum cap, drying tube, magnetic stirrer, and gas inlet. The flask was wrapped in foil and immersed in an ice bath. Chlorine was allowed to bubble through the

solution for 30 min. Aliquots were taken periodically and chromatographed on the vapor phase chromatograph. A ratio of 2.08:1 was found for the diaxial to the diequatorial isomer.

c. in chlorobenzene: Trans-Δ^2-octalin (1 g) was dissolved in chlorobenzene (9 ml) and added to anthracene (0.05 g) in a three necked flask and chlorinated as with pentane as solvent. Aliquots were taken and a ratio of 1.67:1 for the diaxial to the diequatorial dichloride was determined. The solvent was removed from the reaction mixture under reduced pressure on the rotary evaporator. The products were separated by chromatographing the solution in pentane over alumina.

The chromatography using pentane as the carrier was followed with the vapor phase chromatograph. Complete separation of both isomers was obtained. The diaxial isomer came off the column rapidly with pentane. The diequatorial isomer followed but was speeded up by eluting with a pentane-benzene mixture. The diaxial isomer was recrystalized twice from pentane by cooling the solution to dry ice temperatures and a constant melting point (59-60°) was obtained. The diequatorial isomer remained a liquid at room temperature and could not be crystalized.

d. in dichloromethane: Trans-Δ^2-octalin (1 g), anthracene (0.1g) and dichloromethane (15 ml) were chlorinated as with pentane as solvent. The solvent was removed from both the aliquots and the reaction mixture leaving crystals. The crystals were assumed to be primarily anthracene or chloroanthracenes and

were washed with pentane. The pentane solution from the aliquots was chromatographed on the vapor phase chromatograph and gave a ratio of 1.72:1 for the diaxial to the diequatorial isomer. The solution from the reaction mixture was chromatographed over alumina as above.

Trans-Δ^2-octalin (0.2g), anthracene (0.1 g), and dichloromethane (15 ml) were chlorinated as with pentane as solvent except a dry ice-acetone bath replaced the ice bath. The solvent from the resulting yellow solution was removed on the rotary evaporator to give white crystals which were washed three times with pentane. The pentane solution was chromatographed on the vapor phase chromatograph and gave a ratio of 1.85:1 for the diaxial to the diequatorial isomer.

e. in carbon tetrachloride: Trans-Δ^2-octalin (0.1 g), anthracene (0.1 g), and carbon tetrachloride (13 ml) were chlorinated as with pentane as solvent. The solvent was removed from the reaction mixture on the rotary evaporator and the residue washed with pentane. The pentane solution was chromatographed on the vapor phase chromatograph and four traces gave an average of 1.89:1 for the ratio of diaxial isomer to diequatorial isomer.

f. in acetic acid: Trans-Δ^2-octalin (approximately 0.1 g), glacial acetic acid (10 ml) and anthracene (0.05 g) were added to a one necked round bottom flask. The flask was wrapped in foil and cooled in an ice bath. Chlorine gas was

allowed to flow through the solution for half an hour. At the end of that time the reactants were found to be frozen. They were warmed to room temperature and chlorine gas wass allowed to flow through the solution for twenty minutes more. The reactants were poured into water (15 ml) and extracted once with pentane (15 ml). The pentane was removed on the rotary evaporator and a sample of the remaining liquid was chromatographed on the vapor phase chromatograph.. The remaining liquid was washed with sodium bicarbonate solution and then chromatographed on the vapor phase chromatograph. The base washed sample showed a great reduction in the acetic acid peak but both samples showed several new peaks upon chromatography which had not previously been observed. These new peaks could be from the products of the addition of acetate to the octalin.. A ratio of 1.42:1 was found for the diaxial to the diequatorial isomer.

Chlorination of trans-diaxial-2,3-dichloro-trans-decalin:

Trans-diaxial-2,3-dichloro-trans-decalin (0.1 g) was dissolved in pentane (15 ml) and chlorinated as with pentane as solvent for 90 min. Chromatography on the vapor phase chromatograph showed no isomerization of the diaxial product.

Chlorination of trans-diequatorial-2,3-dichloro-trans-decalin:

Trans-diequatorial-2,3-dichloro-trans-decalin (approximately 5 drops), anthracene (0.1 g), and pentane (10 ml) were chlorinated as with pentane as solvent for one hour. Chromatography on the vapor phase chromatograph showed only the diequatorial isomer.

Dechlorination of trans- diaxial and trans-diequatorial-2,3-dichloro-trans-decalin.

A mixture of the trans-diaxial and the trans- diequatorial-2,3-dichloro-trans-decalins (approximately 0.1 g total of a 1:1 mixture) was added to glacial acetic acid (14 ml). Zinc (1 g) was added portionwise, and the mixture was heated on the steam bath for 90 min. No reaction had resulted at the end of that time. The acetic acid solution was decanted from the zinc and poured into a flask equipped with a mechanical stirrer. Zinc (2 g) was added portionwise and the mixture heated on the steam bath for $4\frac{1}{2}$ hr. At intervals aliquots were poured into water and extracted with pentane. The pentane extract was chromatographed on the vapor phase chromatograph. At the end of $4\frac{1}{2}$ hr nearly all the trans-diaxial isomer had dechlorinated to give one new peak with the same retention time as that of pure trans-Δ^2-octalin. The reaction flask was equipped with a magnetic stirrer and more acetic acid (17 ml during the reaction as needed) and zinc (0.5 g) were added. The mixture was refluxed for 90 min and during this time the ratio of peak heights of the trans-Δ^2-octalin and the diequatorial-dichloride did not change.

Determination of the yield of the chlorination of trans-Δ^2-octalin in dichloromethane.

Trans-Δ^2-octalin (approximately 0.2 g) and anthracene (0.05 g) were dissolved in dichloromethane in a 10 ml volumetric flask to

give 10 ml of solution. Two aliquots (0.5 ml) were removed and chromatographed on the vapor phase chromatograph. The remaining solution was transfered to a reaction flask and the volumetric flask was rinsed several times with dichloromethane. The solution was then chlorinated as with pentane as solvent. The solvent was removed on the rotary evaporator and the residue was washed into a 10 ml volumetric flask and diluted to 10 ml. Vapor phase chromatography of the products gave a ratio of 0.65:1 for the sum of the areas of the dichlorodecalin peaks to the area of the original trans-Δ^2-octalin peak. Thus a yield of $0.65 \times \frac{10}{9}$ or 72% was determined.

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