reaches the surface (and the active sites there).

The most interesting possibility may be that the rate of reaction of R$^\bullet$ at Mg$_Z$ is controlled by a requirement of solvent or other reorganization of the medium. Bickelhaupt has given evidence in a special case that the mechanism of conversion of R$^\bullet$ to RMgX may involve an initial reduction of R$^\bullet$ to a carbanion (or carbanionoid species) R$^-$, which is then converted to RMgX.[22] The rates of reactions that drastically redistribute charge (such as an oxidation or reduction) can be especially sensitive to the extents and rates of reorganization of the solvent.[23,24] In principle, the reorganization need not be limited to the solvent. It could include ionic aggregation or dissociation, for example. Such reorganization could be R-structure-independent and could largely determine the value of δ.

Summary. The important findings and implications include the following.

(1) The extent of solvent attack by a typical alkyl radical intermediate (Hx$^\bullet$) is clarified. The upper limit of 0.5 mol is consistent with the prediction (ca. 0.12 mol) of the D Model.[2a]

(2) CpBr gives 20–30 mol of CpH derived from the attack of Cp$^\bullet$ on diethyl ether, accompanied by other solvent-derived products (CpS, SS, and S(−H)) as well as CpMgBr. It is clear that CpBr does not behave as a typical alkyl bromide and that **1**, which is reported to give much less solvent attack, does not behave as a typical cyclopropyl bromide, much less a typical alkyl bromide. Conclusions drawn from studies of **1** and similar halides should not be extended to either typical cyclopropyl halides or typical alkyl halides.[3]

(3) The data for CpBr and HxBr falsify the combination of hypotheses (1) that adsorbed radicals do not react with the solvent, (2) that radicals that leave the magnesium surface *do* react with the solvent, and (3) that σ radicals (such as Cp$^\bullet$) are more strongly adsorbed than π radicals (such as Hx$^\bullet$).

(4) A D-Model analysis of the data for CpBr indicates a value of k_S for Cp$^\bullet$ near 10^6 s^{-1}, about 10^3 larger than the value for Hx$^\bullet$. This agrees with estimates based on other data.[8]

(5) The values of δ for Cp$^\bullet$ and Hx$^\bullet$ derived from the data are similar. The lack of dependence of δ on radical structure could be a consequence of (1) diffusion control (with sparsely distributed reactive sites on Mg$_Z$), (2) rate-limiting desorption of some species to make reaction sites available, or (3) rate control by reorganization in the medium, accompanying the reduction of R$^\bullet$ to R$^-$ (or some related process that drastically redistributes charge).

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Viscosity-Dependent Cage Reactions. Multiple Substitutions in Radical-Chain Chlorinations[1]

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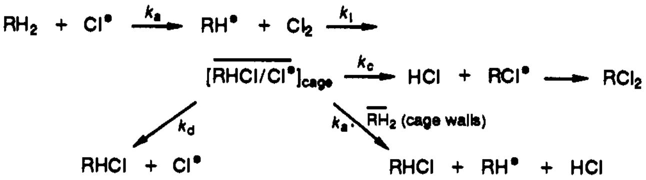
Abstract: The mechanism by which the free-radical chlorination of alkanes produces polychlorides has been explained by the assumption that the geminate chlorine atom–chloroalkane pair react in their solvent cage at rates competitive with their diffusion from, and rotation in, the cage in which they are born. The major piece of evidence supporting this mechanism is that as the concentration of alkane is increased, polyhalogenation decreases. As the hydrocarbon that makes up the "cage walls" becomes more concentrated, the surrounding hydrocarbon scavenges the caged chlorine atoms before they react with their geminate chloroalkane. In the inert solvents in which these reactions take place, CCl$_4$ or various Freons, the viscosity of the solvent is decreased with increasing concentration of hydrocarbon, and the diffusion rates are therefore increased. The diffusion dependence (i.e., viscosity) of the amount of polychlorination is an important component of the observed concentration dependence. The influence of the changing viscosity upon the production of polychlorination becomes more important as the hydrocarbon (neopentane, 2,3-dimethylbutane, or cyclohexane) makin up the cage walls becomes less reactive. The viscosity dependence of cage rotation was observed in solvents of high viscosity for the least reactive hydrocarbon, neopentane.

Introduction

Several years ago Skell[6] recognized that geminate cage halogenation could account for the anomalously high amounts of polychlorinated alkanes produced in the solution-phase photochlorinations of a number of hydrocarbons. Since the substitution reactions of chloroalkanes are less favorable than those of their parent hydrocarbons,[7] the large amount of polychlorination made it appear that the chlorination of a chloroalkane was not deactivated.

Scheme I



When the chlorinations of the hydrocarbons cyclohexane, isobutane, neopentane, or 2,3-dimethylbutane were carried out

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in nonreactive solvents, CCl_4 or $CFCl_3$, unexpectedly large portions of multichlorinated products were obtained.[6] When the chlorinations were carried out to the same percentage conversion but at varying concentrations of hydrocarbon, the ratio of monohalogenation/polyhalogenation, [M]/[P], decreased as the concentration of hydrocarbon increased.[6] The experimental observations were rationalized by the suggestion that a cage reaction takes place between the chloroalkane and the geminate chlorine atom after this pair is formed by the chain-transfer reaction of an alkyl radical with molecular chlorine. The dependence of the [M]/[P] ratio upon the initial concentration of the alkane was rationalized as being due to the facts that as the concentration of hydrocarbon was increased, the walls of the cage contained more RH molecules and that the caged chlorine atoms were scavenged from their geminate pair by the cage walls. The reaction sequence was subsequently amplified and refined by Skell,[8] Ingold,[9] and Tanko[10] (see Scheme I). A simple kinetic analysis[9,10] of the reactions in Scheme I predicts a linear dependence for the mono-polychlorination ratios, [M]/[P], as a function of hydrocarbon concentration The kinetic derivation assumes that the

$$[\mathrm{M}]/[\mathrm{P}] = \frac{k_{\mathrm{d}} + k_{\mathrm{a'}}[\overline{\mathrm{RH}}]}{k_{\mathrm{c}}[\overline{\mathrm{RCl}}]} \tag{1}$$

rate of diffusion is a constant, and that the concentration of the hydrocarbon in the caged walls, $[\overline{\mathrm{RH}}]$, is proportional to the mole fraction of hydrocarbon in solution. It was reported that for some substrates a plot of the substrate concentration vs the [M]/[P] ratio was not linear as the model predicted.[9,10] The deviation from linearity was rationalized as being due to competition between monochloride rotation and reaction of the chlorine atom with hydrocarbon molecules in the "cage walls" surrounding the chlorine atom–alkyl chloride geminate pair. Rotation of the caged chloroalkane was felt to be a necessary condition to provide a site for the cage reaction to take place.

In order to observe the effect of a cage reaction the cage must contain two nonconnected species that can react on a time scale that is competitive with the diffusion of one of the entities out of the cage.

Quite a number of years ago we reported that this requirement was fulfilled during the bromination of an alkane with molecular bromine[12,13] (see eq 2). It was shown that $k_{-1} \approx k_{\mathrm{d}}$.[12,13] When

$$\mathrm{RH} + \mathrm{Br}^{\bullet} \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} \overline{(\mathrm{R}^{\bullet}/\mathrm{HBr})}_{\mathrm{cage}} \underset{k'_{-1}}{\overset{k_{\mathrm{d}}}{\rightleftharpoons}} \mathrm{R}^{\bullet} + \mathrm{HBr} \tag{2}$$

the reactions were carried out at very high concentrations of liquid bromine (10–18 M), where the cage walls are made up of molecular bromine, all of the caged radicals were scavenged, i.e., no reactions with HBr took place.[12] More recently we reported that the diffusion rates, k_{d}, of these caged species are controlled by changing the viscosity of the media. A number of anomalous results were clarified by using this technique.[14-16] The observed multichlorination appears to be another example of the same type of behavior, i.e., where the reaction of a molecule–radical pair is competitive with diffusion of the radical from the cage. The chlorination reaction appears to be amenable to study using solvent viscosity to manipulate the diffusion rates.

Table I. Chlorination of Neopentane. Mono-/Polychlorination Ratios of Products ($RH/Cl_2 > 40/1$, 23 °C, Freon 113)

$[\text{neo-}C_5H_{12}]$	$(\eta_i/\eta_{\text{Freon 113}})$[a]	[M]/[P][b]	[1,3]/[1,1][f]	$[C_5H_9Cl_3]/[C_5H_{10}Cl_2]$
1×10^{-3} [d,e]			3.07 ± 0.11	0.0
3.60	0.70	13.2[c]		
3.60	0.70	13.16[d]		
2.80	0.76	11.4[c]		
2.50	0.79	10.81[d]	3.01 ± 0.19	0.02
1.55	0.88	5.4[c]		
1.00	0.93	4.8[c]		
	0.94	3.33[d]	3.40 ± 0.06	3.33
0.10	1.00	1.8[c]		
0.10	1.00	1.90[d]	3.72 ± 0.14	
0.05	1.03	1.6[c]		

[a] The viscosity of the reaction mixture relative to pure Freon 113. [b] The ratio of mono-/polychlorinated neopentane. The values from this work are the average values obtained from three independent experiments. [c] Taken from ref 10. [d] This work. [e] Vapor-phase chlorination of chloroneopentane. [f] The ratio of 1,3-/1,1-dichloro-2,2-dimethylpropane.

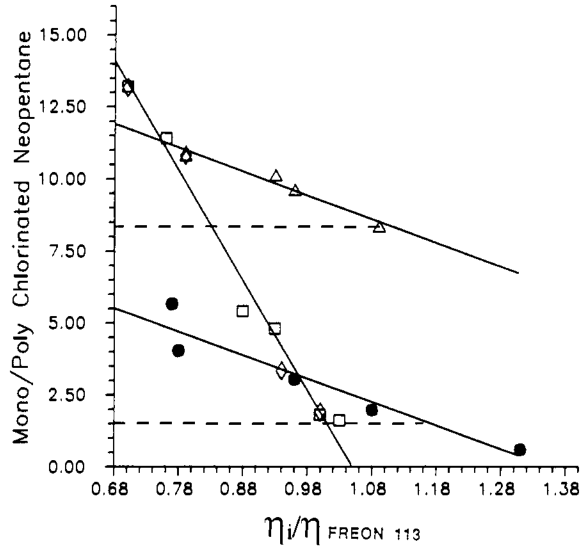

Figure 1. Plot of the ratio [M]/[P] chlorinated neopentane at different concentrations vs the relative viscosities of the solutions in which the reactions are run. ([M]/[P]) values taken from ref 10 vs the viscosities of the reaction mixtures, □. This work ◇. A plot of [M]/[P] chlorinated neopentane (0.84 M, ●; 2.5 M, △) in Freon solvents of different viscosities vs the relative viscosities of the reaction mixtures.

Results and Discussion

Chlorination of Neopentane. When neopentane was chlorinated in solvent Freon 113, the ratio of mono-/polychlorinated neopentane was found to increase linearly as the concentration of neopentane increased. A plot of the ratio of mono-/polyhalogenated substrate vs the concentration of neopentane was identical to that reported by Tanko.[10] However, as the concentration of neopentane was progressively increased, the viscosity of the solutions also decreased linearly (see Table I). The linear correlations are presented graphically in Figure 1. When the chlorinations were carried out at a constant concentration of neopentane (0.84 or 2.50 M) in Freon solvents of varying viscosity, plots of the ratio of mono-/polyhalogenated products vs viscosity were also linear (Table II, Figure 1). The change in the [M]/[P] chlorination ratio, $\Delta([\mathrm{M}]/[\mathrm{P}])_{\mathrm{vis}}$, that is due solely to changes in viscosity can be estimated by comparing $\Delta([\mathrm{M}]/[\mathrm{P}])_{\mathrm{cc}}$ for the reactions carried out at constant concentration with $\Delta([\mathrm{M}]/[\mathrm{P}])_{\mathrm{vc}}$ obtained for the reactions carried out at varying concentration. Over the concentration and viscosity ranges plotted, the change

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Table II. Chlorination of Neopentane (0.84 and 2.50 M) in Solvent Freons of Variable Viscosities

solvent	neopentane (0.84 M) $\eta_i/\eta_{\text{Freon 113}}$[a]	neopentane (0.84 M) [M]/[P][b]	neopentane (2.50 M) $\eta_i/\eta_{\text{Freon 113}}$[a]	neopentane (2.50 M) [M]/[P][b]
Freon 11	0.77	5.65 ± 0.23		
Freon 11/Freon 113 (50/50)	0.78	4.03 ± 0.22		
Freon 113	0.96	3.03 ± 0.22	0.79	10.81 ± 0.71
Freon 113/Freon 112 (50/50)	1.08	1.96 ± 0.08	0.93	10.12 ± 0.49
Freon 113/Freon 112 (65/35)			0.96	9.62 ± 1.40
Freon 112	1.31	0.59 ± 0.04	1.09	8.34 ± 0.16

[a] The viscosities of the reactant mixtures relative to the viscosity of pure Freon 113. [b] The ratio of mono-/polychlorination products.

Table III. Isomer Distribution for the Solution-Phase Chlorination of Neopentane and the Vapor-Phase Chlorination of Neopentyl Chloride ([Substrate]/[Cl_2] > 40/1, 23 °C)

solvent	reactants $\eta_i/\eta_{\text{Freon 113}}$[a]	reactants [neopentane]	products [1,3-dichloride]/[1,1-dichloride][b]	products [$Cl_3C_5H_9$]/[$Cl_2C_5H_{10}$]
vapor phase		1×10^{-3}	3.07 ± 0.11	
Freon 11	0.77	0.84	3.63 ± 0.16	0.02
Freon 11/Freon 113 (1/1)	0.79	2.50	3.01 ± 0.19	
Freon 113	0.96	0.86	3.40 ± 0.06	0.03
Freon 112/Freon 113 (1/1)	1.08	0.86	3.36 ± 0.24	0.01
Freon 112	1.31	1.00	2.70 ± 0.08	0.02

[a] The viscosities of each solution relative to pure Freon 113, 23 °C. [b] The mean value of three separate reactions. The errors are deviations from the mean value.

Table IV. Chlorination of DMB at Varying Concentrations in CCl_4 ([DMB]/Cl_2 > 17, 23 °C)

[DMB]	mole fraction	η_i/η_{CCl_4}[a]	[M]/[P][b,c]
7.59	1	0.361	24.17 ± 0.57 (3)
6.27	0.78	0.454	16.64
5.00	0.585	0.542	12.02
3.00	0.326	0.682	6.71
1.00	0.101	0.824	2.91
0.50	0.05	0.883	1.13

[a] The relative viscosities of the solution relative to pure CCl_4, 23 °C. [b] Mono-/polychlorinated ratio of products. [c] Values in parentheses are the number of independent reactions.

Table V. Chlorination of DMB at Varying Concentrations in Freon 112 ([DMB]/[Cl_2] > 17, 23 °C)

[DMB]	mole fraction	$\eta_i/\eta_{\text{Freon 11}}$[a]	[M]/[P][b,d]
0.50	0.062	1.811	1.75 ± 0.24 (4)
1.00	0.143	1.674	4.31 ± 0.85 (4)
2.00	0.252	1.412	5.66 ± 0.19 (4)
4.00[c]	0.511	1.07	7.97 ± 1.11 (4)
6.50	0.846	0.706	15.90 ± 0.90 (4)
neat	1.00	0.548	24.17 ± 0.84 (3)

[a] The viscosity of the reaction mixtures relative to pure Freon 11. [b] The ratio of mono-/polychlorinated DMB. [c] [DMB] = 4.00 M; $\eta_i/\eta_{\text{Freon}}$ = 0.769; [M]/[P] = 9.78 (solvent Freon 11). [d] Values in parentheses are the number of independent reactions.

in the amount of polychlorination due to a change in viscosity, $\Delta([M]/[P])_{vis}$, was responsible for a significant fraction of the [M]/[P] ratio (i.e., the difference between $\Delta([M]/[P])_{vc}$ and $\Delta([M]/[P])_{cc}$).[11] At low concentrations of hydrocarbons (such as 0.84 M), 23% of the change in the [M]/[P] ratio was not due to a change in the concentration of the substrate hydrocarbon, but was due to changes in the solution viscosity. At higher concentrations of neopentane (such as 2.50 M, at lower viscosity), 65% of the effect on the [M]/[P] ratio of changing the concentration is due to changing the viscosity of the media.

The rotational dependence of the cage-chlorination products was examined as a function of the viscosity. The ratio 1,1-/1,3-dichloroneopentane for vapor-phase halogenation of monochloroneopentane and the solution-phase chlorination of neopentane in Freon solvents of varying viscosity are listed in Table III. The ratios of dichlorinated products obtained from reactions carried out with different concentrations of neopentane are also listed in Table I. The ratio of the two dichlorinated products is only indicative of a rotational dependence of the rate of reaction if trichlorination is not important. In the reactions listed, the trihalogenated products are not produced in a significant amount to interfere with the determination of the ratio of the two products (see Tables I and III). The ratio of the products formed from free encounter of the chlorine atom with neopentyl chloride, 1,3-dichloroneopentane/1,1-dichloroneopentane (3.07 ± 0.11), appeared to be experimentally indistinguishable from most of the values obtained in the solution-phase halogenation. Only in the case of the chlorinations carried out in the most viscous solvents, Freon 112 or 113, at low concentrations of hydrocarbon was 1,1-dichlorinated neopentane produced in a significantly higher yield compared to the yield of 1,3-dichlorinated neopentane. This observation is consistent with a rapid reaction of the caged neopentyl chloride–chlorine atom pair which takes place faster than the rotation of the neopentyl chloride in a viscous media. The observation that the isomer distribution may be affected by viscosity is consistent with the experimental observation made by Tanko[10] that the concentration affected the isomer distribution of the dichlorides.

The effect of viscosity on relative product distributions has been reported previously when the combination/disproportionation reactions of caged *tert*-butyl radicals were studied.[7] Although the relative reactivity of combination/disproportionation reactions was affected by changes in viscosity, only at very high viscosities could differences be observed between the rotational-dependent reactions of encounter pairs and caged pairs. The rotation of neopentyl chloride in the cage reaction leading to polychlorination is predictably more sensitive to viscosity-impeded rotation than is the more symmetric *tert*-butyl radical.

Chlorination of DMB. Solutions of 2,3-dimethylbutane (0.5–7.6 M) were chlorinated in solvents carbon tetrachloride and Freon 112 (see Tables IV and V). As the concentration of substrate increased, the ratio of mono-/polychlorination decreased. As in the case of the chlorination of neopentane, as the concentration of DMB was increased, the viscosity of the solutions decreased. The viscosity of the solutions are also listed in Tables IV and V. Plots of the concentration of DMB vs the ratio of mono-/polyhalogenated products for reactions carried out in both carbon tetrachloride and Freon 112 are displayed in Figure 2. As previously reported[9a,d] for chlorination carried out in CCl_4, a plot of the mole fraction of [DMB] vs the ratio of [M]/[P] was not linear. The same behavior is found for reactions run in Freon. The curvature in both plots is only noticeable at very high concentrations of DMB (>80 mol %) where the reactions are carried

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Table VI. $\eta_i/\eta_{\text{Freon 11, 23 °C}}$ vs Mono-/Polychlorinated DMB (0.25 M)[a]

solvent	$\eta_i/\eta_{\text{Freon 11, 23 °C}}$	[M]/[P][b,c]	[D]/[T][b,c]	[T]/[P] (%)[b,c]
vapor phase	0.028	181.8		
Freon 11	0.963	1.78 ± 0.06	4.38 ± 0.43	18.6
Freon 11/Freon 113 (1/1)	1.059	1.49 ± 0.02	3.63 ± 0.33	21.6
Freon 113	1.227	1.07 ± 0.15	3.16 ± 0.08	24.0
Freon 11/Freon 112 (1/1)	1.247	0.987 ± 0.06	2.80 ± 0.06	26.3
Freon 113/Freon 112 (1/1)	1.464	0.770 ± 0.03	2.68 ± 0.21	27.2
Freon 112	1.868	0.584 ± 0.01	2.23 ± 0.24	31.0

[a] $[\text{DMB}]/[\text{Cl}_2] > 17$. [b] The average value of three or more individual experiments. The errors are deviations from the mean value. [c] The ratio of mono-/polychlorinated DMB, [M]/[P]; dichloro-/trichloro-DMB, [D]/[T]; and trichloro-/polychlorinated DMB, [T]/[P] (%).

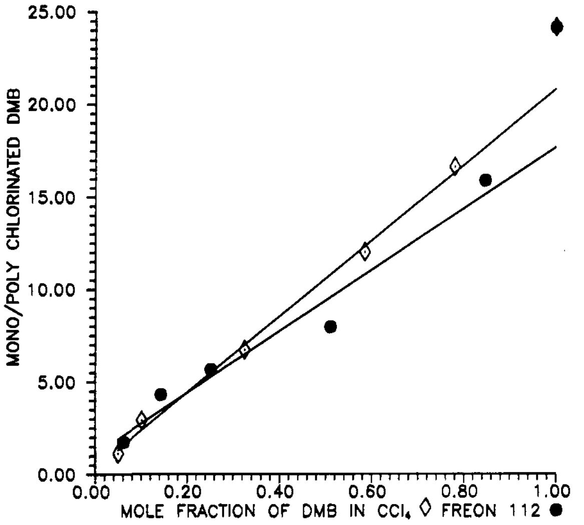


Figure 2. Plot of the [M]/[P] chlorinated DMB vs the mole fraction of DMB in CCl_4 (◇) and Freon 112 (●).

out essentially without solvent. The curvature in the plot was originally ascribed to a competition for the caged chlorine atom between the hydrocarbon that makes up the caged walls and the necessity for rotation of the caged alkyl halide prior to its ability to react. However, since the viscosity of the solution decreases as the concentration of DMB increases, it is clear that the diffusion rate, k_d, does not remain constant. Since the diffusion rate is inversely proportional to the solvent viscosity, eq 1 is related to viscosity by the diffusion coefficient, α (see eq 3). A plot of the

$$[\text{M}]/[\text{P}] = \frac{\alpha/\eta + k_{a'}[\overline{\text{RH}}]}{k_c[\overline{\text{RCl}}]} \tag{3}$$

data fit to eq 3 does not demand linearity since the diffusion coefficient and the viscosity are expected to change as the composition of the media changes. Curvature of these types of plots is not, therefore, diagnostic of the rotational requirement for the reaction of the caged alkyl halide, while linearity of the plots may only be fortuitous. A straight line can be approximated for the data obtained from reactions carried out in solvent containing less than 60 mol % of DMB. The viscosity dependence of the mono-/polychlorinated DMB was determined for chlorinations carried out in Freon 112 with varying concentrations of DMB (Table V) and for reactions carried out in solutions of DMB (0.25 and 4.00 M) in Freon solvents of varying viscosity (Tables V and VI). The relationship between the halogenation products and the viscosity of the solution for these three sets of reactions (Tables V and VI) is displayed in Figure 3. A comparison of the values of Δ([M]/[P]) for the three linear plots of [M]/[P] vs viscosity[11] of the reaction mixtures at concentrations of <50 mol % DMB indicated that at low concentrations (such as 0.25 M) of DMB only (1.6/10.1) 18% of the ratio was determined by the viscosity of the reaction mixture, while at 4.00 M DMB 55% of the change in ratio, Δ([M]/[P]), was determined by the viscosity of the solvent.

The distribution of dichlorinated DMB has been reported previously for reactions carried out in the solvent CCl_4 (0.5 M in DMB), and in neat DMB.[9a] The percentages of trichlorinated/dichlorinated products, ([T]/[D]) × 100, were almost the same as those obtained from the reactions carried out in Freon. The rotational dependence of the isomer distribution as a function of viscosity could not be determined since any observable difference in the isomer distribution of the dichlorides was masked by the production (18–31 %) of trichlorinated DMB (see Table VI).

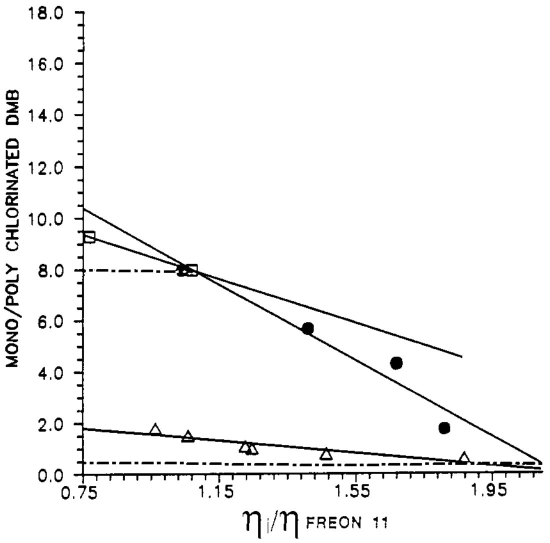


Figure 3. Plot of the ratio of [M]/[P] chlorinated DMB at varying concentrations in solvent Freon 112 vs the relative viscosities of the solutions. The [M]/[P] ratio of chlorinated DMB solutions (0.25 M, Δ; 4.0 M, □) in Freon solvents of varying viscosities (see Table V (●, □) and Table VI (Δ)).

Table VII. Chlorination of Cyclohexane in Freon 112, 23 °C[a]

$[\text{C}_6\text{H}_{12}]$	mole fraction	$\eta_i/\eta_{\text{Freon 11}}$[b]	[M]/[P][c,d]
0.50	0.062	1.914	0.74 ± 0.13
1.00	0.143	1.867	2.54 ± 0.08
3.00	0.252	1.665	8.10 ± 0.32
5.00	0.511	1.542	16.38 ± 0.80
7.00	0.846	1.394	28.2 ± 3.2
8.98	0.964	1.279	40.64 ± 1.21
neat	1.00	0.798	45.37 ± 2.36

[a] $[\text{C}_6\text{H}_{12}] = 5.00$ M; $\eta_i/\eta_{\text{Freon 11}} = 1.001$; $[\text{M}]/[\text{P}] = 19.2 \pm 1.6$. [b] The viscosity of the reaction mixtures relative to pure Freon 11. [c] The ratio of mono-/polychlorinated products. [d] The mean values of three or more individual reactions. The errors quoted are deviations from the mean values.

Table VIII. Photochlorination of Cyclohexane in CCl_4, 23 °C ($[\text{C}_6\text{H}_{12}]/[\text{Cl}_2] > 17$)

$[\text{C}_6\text{H}_{12}]$	mole fraction	$\eta_i/\eta_{\text{CCl}_4}$[a]	[M]/[P][b]
0.50	0.049	0.962	1.47
1.00	0.098	0.929	2.38
3.00	0.303	0.887	5.06
5.00	0.518	0.849	8.06
7.00	0.743	0.801	15.05
9.17	1.00	0.798	45.37

[a] The viscosities of the reaction mixtures relative to that of pure CCl_4. [b] The ratio of mono-/polychlorinated cyclohexane. Average values of multiple analyses of single experiments.

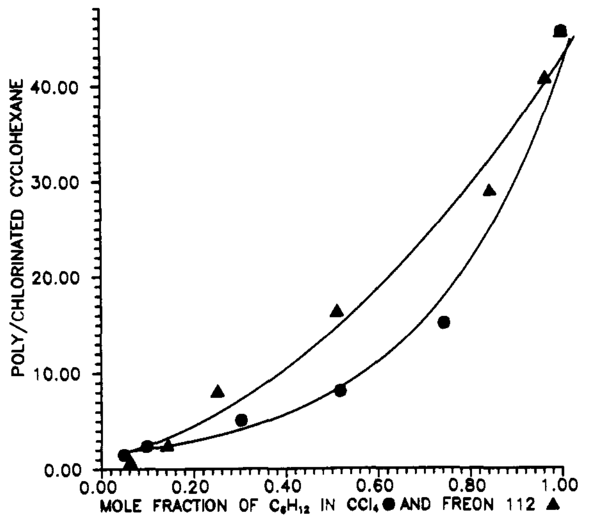


Figure 4. Plot of the [M]/[P] chlorinated cyclohexane vs the mole fraction of cyclohexane in CCl_4 (●) and in Freon 112 (▲).

Table IX. $\eta_l/\eta_{\text{Freon 11, 23 °C}}$ vs Mono-/Polychlorinated Cyclohexane (0.25 M)

solvent	$\eta_i/\eta_{\text{Freon 11, 23 °C}}$[a]	[M]/[P][b]	[D]/[T][c]
vapor phase	0.028	92.8	
neat	0.798	45.37	
Freon 11	0.98	1.40	0.776
Freon 11/Freon 113 (1/1)	1.07	0.998	0.716
Freon 113	1.24	0.638	0.639
Freon 113/Freon 112 (1/1)	1.48	0.584	0.586
Freon 112	1.87	0.296	0.498

[a] The viscosity of the reaction mixtures relative to pure Freon 11. [b] The ratio of the mono-/polychlorinated cyclohexane. The values reported are the average values of three independent experiments. [c] The ratio of dichlorinated cyclohexane/trichlorinated cyclohexane.

Chlorination of Cyclohexane. The chlorinations of cyclohexane at varying concentrations were carried out in Freon 112 and in carbon tetrachloride. The mono-/polychlorination ratios were determined (Tables VII and VIII). A plot of the mole fraction of cyclohexane vs mono-/polyhalogenation is given in Figure 4. In solvent CCl_4, as previously reported,[9] a curved function was obtained. As the concentration of cyclohexane was increased in CCl_4, the viscosity of the solutions decreased (see Table VIII). In Freon 112 the plot of the [M]/[P] ratio vs the concentration of cyclohexane shows a less steeply curved correlation than that obtained for the reactions carried out in CCl_4. The smaller curvature is similar to the linear relationship obtained for the other symmetric hydrocarbon, neopentane. Also in the Freon 112 solutions as the concentration of cyclohexane increased, the viscosity decreased (see Table VII). A plot of the concentration of the ratio of the mono-/polyhalogenated materials vs the viscosity of the solutions for the reactions carried out in Freon solution is displayed in Figure 5. Chlorinations of cyclohexane at constant concentrations (0.25 and 5.0 M) were carried out in solutions of Freons of variable viscosity. The ratio of mono-/polyhalogenated cyclohexane decreased as the viscosity of the solvent increased (Tables VII and IX). The viscosity dependence of multihalogenation is illustrated in Figure 5.

A comparison of the changes in the [M]/[P] ratio, $\Delta([M]/[P])_{cc}$ and $\Delta([M]/[P])_{vc}$, of the three linear correlations indicates that at low concentration (0.25 M) or high concentration (5.0 M) of cyclohexane, the contribution to the mono-/multihalogenation ratio due to viscosity, $\Delta([M]/[P])_{vis}$, is very small (~5%).

The dependence of the isomer distribution of the dihalogenated cyclohexanes in Freon solvents of varying viscosity is listed in Table X. The true distribution of dihalogenated products obtained for the reactions carried out in Freon solution was masked by the large quantity of trihalogenated products formed ([D]/[T] > 0.5) (see Table IX). The isomer distribution of dichlorinated cyclohexanes for chlorinations carried out in neat cyclohexane was, within experimental error, the same as that previously reported.[9a] Only in neat cyclohexane could a comparison be made between the dichlorinated product formed in solution, with the isomer distribution expected for the reaction of cyclohexyl chloride–chlorine atom encounter pairs formed during the vapor-phase chlorination of cyclohexyl chloride. In neat cyclohexane the relative distribution of products formed at the 1,3 and 1,4 positions is lower than those expected to be formed from the reaction of encounter pairs. In solution the decreased ratios of 1,3 and 1,4 dichlorides over those predicted for reactions carried out in the absence of cage reactions (i.e., the vapor-phase chlorination of cyclohexyl chloride) are consistent with the explanation put forward by Ingold,[9a] that in solution rotational impedance of the caged species is responsible for the change in isomer distribution.

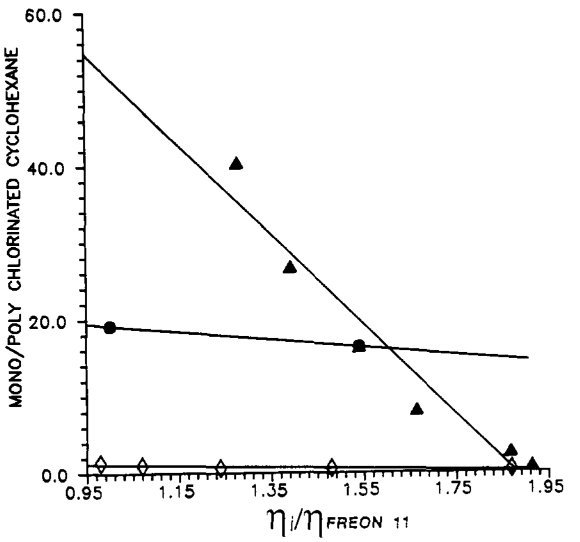
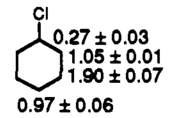
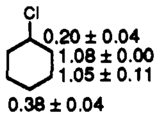


Figure 5. Plot of the ratio [M]/[P] chlorinated cyclohexane at varying concentrations in Freon 112 vs the relative viscosity of those solutions, ▲. The ratio of [M]/[P] chlorinated cyclohexane (◇, 0.25 M; ●, 5.0 M) in Freon solvents of different relative viscosities (see Table VII (●, ▲) and Table IX (◇)).

Table X. Dichlorocyclohexane Isomer Distribution from the Vapor-Phase Photochlorination of Cyclohexyl Chloride and the Solution-Phase Chlorination of Neat Cyclohexane, 23 °C[a]

vapor-phase chlorination of chlorocyclohexane		solution-phase chlorination of cyclohexane (neat, 23 °C)	
dichloro-cyclohexane	rel distribution	dichloro-cyclohexane	rel distribution
1.1-$C_6H_{10}C_{12}$	0.27 ± 0.03	1,1-$C_6H_{10}C_{12}$	0.20 ± 0.04
trans-1,2-$C_6H_{10}C_{12}$	(1.00)	*trans*-1,2-$C_6H_{10}C_{12}$	(1.00)
trans-1,3-$C_6H_{10}C_{12}$	0.56 ± 0.02	*trans*-1,3-$C_6H_{10}C_{12}$	0.44 ± 0.06
trans-1,4-$C_6H_{10}C_{12}$	0.40 ± 0.01	*trans*-1,4-$C_6H_{10}C_{12}$	0.17 ± 0.03
cis-1,3-$C_6H_{10}C_{12}$	1.35 ± 0.05	*cis*-1,3-$C_6H_{10}C_{12}$	0.61 ± 0.05
cis-1,4-$C_6H_{10}C_{12}$	0.57 ± 0.05	*cis*-1,4-$C_6H_{10}C_{12}$	0.20 ± 0.01
cis-1,2-$C_6H_{10}C_{12}$	0.05 ± 0.01	*cis*-1,2-$C_6H_{10}C_{12}$	0.08 ± 0.00
			

[a] The isomer distributions reported are the three average values obtained from three individual experiments. The errors are the average deviation from the mean values.

Conclusion

Abstraction reactions of hydrogen by a chlorine atom in a geminate, RHCl/Cl•, caged pair occur at rates that are competitive with the diffusion of one of the species from the cage. The rate of diffusion from the cage is influenced by the viscosity of the media. In an inert solvent as the concentration of the hydrocarbon is increased, polychlorination is decreased, since the cage walls, made up of increasing amounts of hydrocarbon, can scavenge the caged chlorine atom. However, as the concentration of hydrocarbon (neopentane, 2,3-dimethylbutane, or cyclohexane) is increased, the viscosity of the inert solvents used (Freon or CCl_4) decreases, and the ratio of competitive rates of geminate cage reaction and diffusion also changes. The reactivity of the hycrocarbon determines the viscosity dependence of polychlorination. The reactivity/molecules of neopentane:2,3-dimethylbutane:cyclohexane is 1:1.6:2.7.[18] The effect of diffusion becomes more important in determining the amount of polychlorination that takes place as the cage walls become less reactive. With the least reactive hydrocarbon, neopentane, over the range of concentrations plotted, 23–65% of the [M]/[P] halogenation ratio is due to changes in viscosity. As the walls of the cage become more reactive, as in the case of DMB, viscosity only affects the ratio 18–55%. In the chlorination reactions of cyclohexane the viscosity affected the amount of [M]/[P] halogenation by a negligible amount, ~5%.

The viscosity of the solution can also affect the isomer distribution of the polychlorination products since the rotation of the caged alkyl halide in viscous media becomes competitive with hydrogen abstraction. The ratio of 1,1-/1,3-dichloroneopentane increases in the viscous solvent, Freon 112, compared to the same ratio produced from the free-encounter chlorination of neopentyl chloride.

Experimental Section

Materials. All reagents except Freon 112 were obtained as reagent grade (2,3-dimethylbutane, cyclohexane, neopentane, Phillips research grade) and were distilled before use. Freon 112 (Matheson) was recrystallized several times before use.

Viscosity Measurements. The viscosities of all the solvent mixtures reported in this work were determined at 23 °C with an Ostwald viscometer, calibrated with the appropriate solvent (e.g., Freon 11, Freon 113, or CCl_4) as a standard.[19]

Solution-Phase Chlorination. A mixture of the hydrocarbon, with or without an internal standard (*p*-dichlorobenzene), and solvent was prepared and its viscosity was measured at 23 °C. In the absence of light, an aliquot of this solution and an aliquot of a chlorine solution (in the same solvent) were added to each ampule. The reaction ampules were degassed by freeze–thaw (three cycles), sealed, thermostated at 23 °C, and irradiated with two 150-W incandescent lamps. After the reactions were completed, the product mixtures were analyzed by GC using a 100-m fused silica capillary column (SE-30). The relative product yields from three or more independent experiments were calculated by comparison of their peak integrations to that of the internal standard and corrected for the FID detector response. The areas were determined with use of a Varian Vista 401 computing integrator interfaced to a Varian 6000 gas chromatograph fitted with an FID detector. The mono- and dichlorinated products of neopentane and 2,3-dimethylbutane were identified by comparison of the retention times, GC–MS, spectra and GC–IR spectra with those of authentic samples.

The structures of the products obtained from the chlorination of cyclohexane were assigned by comparison of their GC retention times (i.e., their order of retention) with those reported by Ingold using the same column.[9a] Under our GC conditions all seven of the isomeric dichlorides could be separated. Their GC–MS spectra confirmed their assignments as dichlorides. As an additional confirmation, the retention times of authentic samples of *trans*-1,2-dichlorocyclohexane and chlorocyclohexane were used to check the retention times of the dichlorides, and to calibrate the correction factors used for the FID response factors for the [M]/[P] ratios.

Gas-Phase Chlorinations. In the absence of light, a weighed amount of the hydrocarbon substrate and an aliquot of a chlorine solution in Freon 113 or Freon 11 were added to a 0.5-L reaction vessel. The mixture was degassed by freeze–thaw (two cycles), sealed, thermostated at 23 °C, and irradiated with two 150-W incandescent lamps. After the reactions were completed, the product mixtures were analyzed in the same manner as was used for the solution-phase reactions.

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[18] Russell, G. A. *Free Radicals*; Kochi, J. K., Ed.; Wiley: New York, 1973; Vol. 1.

[19] Daniels, F.; Williams, J. W.; Bender, P.; Alberty, R. A.; Cornwell, C. D.; Harriman, J. E. *Experimental Physical Chemistry*, 7th ed.; McGraw-Hill: New York, 1978; p 164.

(η^6-Arene)chromium Complexes in Organic Synthesis: Synthesis of (±)-Dihydroxyserrulatic Acid

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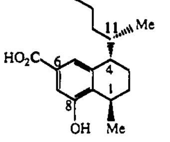
Abstract: The title compound **1** has been synthesized by utilizing some characteristic properties of (η^6-arene)chromium complexes. The synthesis of dihydroxyserrulatic acid (**1**) consists of the following three key steps: (1) nucleophilic addition of a dithianyl group at the meta position to an electron-donating methoxy group, (2) trans arrangement of two benzylic substituents (at C-1 and C-4 positions), and (3) stereocontrol between C-4 and C-11 positions (extracyclic position). These three steps have been realized with high regio- and stereoselectivities by utilizing (arene)chromium complexes.

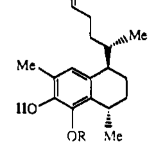
Introduction

Serrulatane class diterpenoids dihydroxyserrulatic acid (**1**),[1] *seco*-pseudopterosins A–D (**2**),[2] pseudopterosins A–D (**3**),[3] and the related compounds[4,5] have been isolated from the leaves of *Eremophila serrulate*, a visid schrub, and marine sea whip *Pseudopterogorgia elisabethae*. Some of these diterpenoids possess the anti-inflammatory and analgesic activity with potencies comparable to that of indomethacin.[6] Moreover, it appears that their mechanism of actions is distinct from that of the cyclooxygenase-inhibiting anti-inflammatory agents, making them particularly fascinating compounds from a biological standpoint.



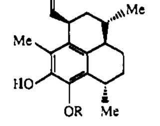
1

Dihydroxyserrulatic acid



2

Seco-pseudopterosins A-D
A; R= arabinose



3

Pseudopterosins A-D
A; R= β-xylose

These compounds have 1,4,6-trisubstituted 8- (or 7,8-di-) hydroxytetralin as a common structural unit and are prenylated

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