motions largely of atoms other than the isotopic ones, they are likely to contribute considerably less to the deviation of eq 8 from unity.

However, the reactant has a pair of frequencies, approximately the symmetric and antisymmetric stretching modes of the two C–C bonds which are broken in the course of the reaction, but the corresponding motions of the transition state include a real vibration involving these two bonds, and the reaction coordinate motion itself. The exact nature of these two transition-state motions depends on whether the mechanism is concerted or stepwise. In the concerted extreme, where $f_{2A}^{\ddagger} \equiv f_{2B}^{\ddagger} \equiv f_2^{\ddagger}$ in eq 8, the reaction coordinate is the symmetric stretch of these two C–C bonds and the anti reaction coordinate is the antisymmetric stretch. For mechanisms which are not concerted, there will be two separate transition states, A and B, differing only in the position of deuterium substitution, in the case of the d_2 species. The concerted extreme will have a single d_2 transition state whose anti reaction coordinate motion is intermediate in frequency between the anti reaction coordinate frequencies of the d_0 and d_4 transition states. As the mechanism loses concertedness and approaches the stepwise extreme, the two d_2 transition states (A and B) must be taken into account. But one of these two will have an anti reaction coordinate frequency close to that of the d_0 transition state (slightly lower), and the other will have an anti reaction coordinate frequency close to that of the d_4 transition state (slightly higher). If the sum rule applies to this group of frequencies, then the anti reaction coordinate frequencies obey the relationship $\omega_0^2 + \omega_4^2 = \omega_A^2 + \omega_B^2$. If $\omega_A \neq \omega_B$, the deviation of eq 8 from unity will be less than for the concerted extreme, where they are equal. However, these antireaction coordinate frequencies will all be similar, for the motion is one which involves primarily carbon atoms and relatively little motion of H and D atoms. While it is true that the reaction coordinate motion—and therefore also the anti-reaction coordinate motion—will be changed in form somewhat by making the unsymmetrical substitution of two D atoms, this problem will also be greatest for the concerted extreme of mechanism (since nonconcerted mechanisms have less coupling of the two C–C stretches, lack of such coupling being the *definition* of nonconcertedness).

In sum, the problems which might arise in eq 8 are delineated by the above discussion. The anti-reaction coordinate motion may be expected to be the worst offender, particularly if the mechanism is concerted. In view of the fact that a concerted mechanism should offer the worst problems, and in view of the fact that we can identify these problems as being associated primarily with normal modes which are not greatly affected by isotopic substitution (being largely C–C stretching modes), it seems that our experimental data, which support a *concerted* mechanism, are a valid indication of mechanism and, as well, an indication that eq 8 is valid.

Free-Radical Halogenation of Adamantane. Selectivity and Relative Lifetime of 1- and 2-Adamantyl Radicals

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Abstract: Free-radical halogenation of adamantane was carried out under nitrogen and oxygen. In the absence of oxygen, the ratios of products, 1-haloadamantane:2-haloadamantane, under different conditions were dramatically dependent on the halogenating reagent employed. Under oxygen, there took place oxygenation as well as normal halogenation. The principal oxygenated product was 1-adamantanol and only traces of 2-oxygenated adamantanes, if any, were formed. These results were interpreted in terms of different lifetimes of 1- and 2-adamantyl radicals and a conclusion is drawn that 1-adamantyl is remarkably more long-lived than 2-adamantyl despite the very indiscriminate behavior of the former radical compared with the latter in the condition of competitive bromination–chlorination. The origin of the present reactivity–selectivity relationship is discussed.

Much effort has been devoted to the investigation of bridgehead radicals in recent years. A criterion for the stability of a bridgehead radical has been based on the observation that the rate of its formation is considerably fast. One point to be made is, however, that there has been no convincing experimental evidence for the parallelism between the facility of the formation of a radical and its stability.

Further complication arises from the polar contribution to the transition state of radical reactions. The transition state of many hydrogen abstraction reactions may be depicted as

$$R\overset{+}{\cdots}H\cdots X^{\delta-}$$

X = Br, Cl, and CCl_3, etc.

owing to the electrophilic nature of the usual hydrogen abstracting radicals (bromine, chlorine, and trichloromethyl, etc.). Even the decomposition of a *tert*-butyl perester, which is commonly used as one of the best ways to assess the stability of a radical,[1] still has some (not

(1) (a) W. A. Pryor, "Free Radicals," McGraw-Hill, New York,

much, estimated to be only 10%) polar character in its transition state.[2] In the case of hydrogen abstraction by electronegative atoms or radicals, the ready formation of a radical is due, to some extent, to the stability of the corresponding carbonium ion.[3]

Prior to the kinetic studies of the thermolysis of a series of bridgehead peresters,[4] it had been suggested that the 1-apocamphyl (7,7-dimethylnorbornyl-1[5]) and 1-bicyclo[2.2.2]octyl[6] radicals were appreciably unstable from the observation that the Hunsdiecker reactions of the corresponding acids in carbon tetrachloride afforded appreciable amounts of the chlorinated products as well as the brominated products. This conclusion was based on the well-known reactivity–selectivity relationship, the validity of which was, however, uncertain.[7] Furthermore, the Hunsdiecker reaction does not seem to reflect exactly the product composition of the inherent radical reaction.

Because of the above-described ambiguities of the procedures for the estimation of the stability of a radical, different conclusions may be obtained by different procedures. A typical example may be the 1-adamantyl radical. The kinetic studies[4] have demonstrated that 1-adamantyl and *tert*-butyl are of essentially identical stability, indicating that 1-adamantyl is an ordinary tertiary radical in conflict with the statement of Applequist and Kaplan,[8] who proposed some extra stabilization in 1-adamantyl to explain easier formation of 1-adamantyl compared with *tert*-butyl by decarbonylation of the corresponding acyl radicals. In contrast, further evidence suggests that *tert*-butyl is much more stable than 1-adamantyl.[9] Thus, all possibilities are represented for the relative stability of 1-adamantyl. In our previous communication,[10] we suggested that 1-adamantyl seemed to be less stable than the normal 2-adamantyl on the basis of the reactivity–selectivity relationship, *i.e.*, 1-adamantyl readily abstracted chlorine from bromotrichloromethane or even from carbon tetrachloride in the presence of a brominating reagent in strong contrast to the very high selectivity of 2-adamantyl.

To shed more light on the nature of 1-adamantyl, further studies seem to be necessary. The present work steps toward the objective of obtaining the relative lifetimes of 1- and 2-adamantyl in solution as a more direct measure of the stabilities of these radicals.

Results

Substitution under Nitrogen. The benzoyl peroxide (BPO) initiated free-radical halogenation on adamantane under nitrogen at 95° afforded 1- and 2-substituted adamantanes. The product distribution (which showed no appreciable change in the course of the reaction) was very much dependent on the halogenating reagent employed (Table I).

Table I. Product Distribution of the Free-Radical Halogenation on Adamantane under Nitrogen at 95° [a]

Reagent	Solvent	% distribution 1-Cl	2-Cl	1-Br	2-Br	Total reactivity ratio (1:2, H/H)
NBS[b]	PhCl			45	55	2.5
CH_2Br_2	CH_2Br_2			75	25	9.0
CCl_4	CCl_4	89	11			24.3
$BrCCl_3$	$BrCCl_3$	5		85	10	27.0

[a] BPO was used as an initiator. [b] *N*-Bromosuccinimide.

In all the cases examined, the bridgehead position has a higher reactivity than the bridge position. As may be seen in Table I, the reaction of adamantane with bromotrichloromethane gives rise to chlorination (only at the 1 position) as well as bromination. Interestingly, the present result[11] is different from that of Gleicher, *et al.*,[3b] who reported that the photoinduced reaction of adamantane with bromotrichloromethane gave no chloroadamantane but gave two oxygenated adamantanes as minor products.[3b] Under our conditions, however, rather simple exclusion of oxygen from nitrogen gas by passing it through an alkaline solution of pyrogallol was sufficient to avoid the contamination by oxygenated adamantanes.[12] The observed selectivity of chlorine abstraction to bromine abstraction by 1-adamantyl from bromotrichloromethane is reasonable in view of the results of Rüchardt, *et al.*[13]

N. Y., 1966, pp 103–111; (b) P. D. Bartlett and C. Rüchardt, *J. Amer. Chem. Soc.*, **82**, 1576 (1960); (c) R. E. Pearson and J. C. Martin, *ibid.*, **85**, 3142 (1963).

(2) ρ^* for the thermolyses of a series of *tert*-butyl 3-substituted peroxyadamantanecarboxylates was reported to be −0.16; Symposium Formation and Chemistry of Adamantanes and Cage-like Hydrocarbons, Division of Petroleum Chemistry, ACS, Houston, Texas, Feb 1970, Preprints, B71.

(3) (a) See pp 170–176 of ref 1a. Most extensively studied has been the benzylic hydrogen abstraction from alkylbenzenes. In most cases, relative reactivities obeyed linear free-energy relationships. ρ values of −1.36 and −0.66 were obtained in the benzylic hydrogen abstraction from substituted toluenes by bromine and chlorine, respectively. Also, see W. D. Totherow and G. J. Gleicher, *J. Amer. Chem. Soc.*, **91**, 7150 (1969). (b) Recently Gleicher, *et al.*, studied the bridgehead hydrogen abstraction from 1-substituted adamantanes by the trichloromethyl radical and suggested the possibility of an appreciable polar contribution to the transition state: P. H. Owens, G. J. Gleicher, and L. M. Smith, Jr., *ibid.*, **90**, 4122 (1968).

(4) (a) J. P. Lorand, S. D. Chodroff, and R. W. Wallace, *ibid.*, **90**, 5266 (1968); (b) R. C. Fort, Jr., and R. E. Franklin, *ibid.*, **90**, 5267 (1968); (c) L. B. Humphrey, B. Hodgson, and R. E. Pincock, *Can. J. Chem.*, **46**, 3099 (1968).

(5) P. Wilder, Jr., and A. Winston, *J. Amer. Chem. Soc.*, **75**, 5370 (1953).

(6) F. W. Baker, H. D. Holtz, and L. M. Stock, *J. Org. Chem.*, **28**, 514 (1963).

(7) Recently this reactivity–selectivity relationship has been verified for the deuterium abstraction from deuterio-*n*-butane by hydrogen atoms at various initial kinetic energies: R. G. Gann, W. M. Ollison, and J. Dublin, *J. Amer. Chem. Soc.*, **92**, 450 (1970). However, the applicability of this relationship to the more complicated carbon radicals may still be open to question. This point will be discussed later.

(8) D. E Applequist and K. Kaplan, *ibid.*, **87**, 2194 (1965).

(9) W. H. Chick and S. H. Ong, *Chem. Commun.*, 216 (1969).

(10) I. Tabushi, J. Hamuro, and R. Oda, *J. Amer. Chem. Soc.*, **89**, 7127 (1967). In this communication, the authors' description on this point was as follows: "The 1 radical is destabilized (relative to its transition state) to a greater extent than is the 2 radical. The extent to which the 1 radical is destabilized may bring its energy either below or above that of the 2 radical." At that time, however, it was impossible to decide which was the case.

(11) The observed yield of 1-chloroadamantane is much smaller than that obtained in our preliminary study.[10] The product distribution is moderately dependent on the reaction condition (it was dependent on drastic changes in the amount of an initiator, the temperature, and especially on conversion).

(12) A referee pointed out that one possible origin of the difference may be the difference in temperatures (40 and 95°) employed in both studies.

(13) It was found that bromine abstraction from bromotrichloromethane by 1-adamantyl was 29 times faster than chlorine abstraction from carbon tetrachloride by the same radical: C. Rüchardt, K. Herwig, and S. Eichler, *Tetrahedron Lett.*, 421 (1969). In our present study, the corresponding ratio of bromine abstraction to chlorine abstraction from bromotrichloromethane by 1-adamantyl is 17 (Table I). The discrepancy in these two values may presumably be due to the enhanced reactivity of chlorine in bromotrichloromethane compared with that in carbon tetrachloride.

As has been pointed out recently,[14] the apparent product distributions of free-radical halogenation do not reflect, in some cases, the kinetically controlled ratios of hydrogen abstraction because of the reversible reaction of the alkyl radicals with hydrogen halide produced in the reaction. To check the possibility of the interconversion between 1-adamantyl and 2-adamantyl *via* the reversible reactions with hydrogen halide, the BPO-initiated NBS bromination was carried out under a vigorous flow of hydrogen bromide or in the presence of sodium carbonate (to destroy hydrogen bromide formed in the reaction). In both experiments, the product ratios of 1-bromo- to 2-bromoadamantane (0.90 and 0.88, respectively) were practically the same as the value in Table I (0.82). These results suggest that there is no appreciable interconversion between 1- and 2-adamantyl in the condition employed, in accord with our preliminary results of the Hunsdiecker reactions of 1- and 2-adamantanecarboxylic acids.[10,15]

Substitution under Oxygen. Although autoxidation of hydrocarbon substrates has been one of the important subjects in free-radical chemistry,[16] there seem to be no systematic studies on the free-radical halogenation in the presence of oxygen.

Halogenation of adamantane was carried out under vigorous oxygen flow at 95° using BPO as an initiator. As might be expected, the adamantyl radical was captured by oxygen to give an appreciable amount of oxygenated product, *i.e.*, 1-adamantanol, although the main reaction was halogenation. Capture of 2-adamantyl would lead to adamantanone.[17] However, neither adamantanone nor 2-adamantanol was obtained in a detectable amount under the present condition. Even for NBS bromination where the bridge hydrogen abstraction was relatively higher than for bromotrichloromethane or carbon tetrachloride, the amount of adamantanone, if any, was less than 1% of 1-adamantanol. These results are noteworthy when taken in conjunction with the published result of the air oxidation of adamantane.[17] It was reported that the cobalt acetate–di-*tert*-butyl peroxide catalyzed air oxidation of adamantane in benzene and glacial acetic acid afforded 1-adamantanol and adamantanone in a ratio of 31:17. Thus, the absence of 2-oxygenated adamantanes in the present reactions seems to reflect the short lifetime of 2-adamantyl radical in the solvent investigated (*vide infra*).

The results are summarized in Table II.

Table II. Product Distribution of Free-Radical Halogenation on Adamantane under Oxygen at 95°[a]

Reagent	Solvent	% distribution				
		1-OH	1-Cl	2-Cl	1-Br	2-Br
NBS	PhCl	14			53	33
CH_2Br_2	CH_2Br_2	6			84	10
CCl_4	CCl_4	12	74	14		
$BrCCl_3$	$BrCCl_3$	30	16		45	9

[a] BPO was used as an initiator.

Bromine Abstraction from 1-Bromoadamantane in Carbon Tetrachloride. The BPO-initiated reaction of 1-bromoadamantane with carbon tetrachloride under nitrogen at 80° afforded two main products, identified as 1-chloroadamantane (28%) and 1-bromo-3-chloroadamantane (72%).

Hunsdiecker Reactions of Adamantanecarboxylic Acids. The Cristol-modified Hunsdiecker reaction[18] of 1-adamantanecarboxylic acid in carbon tetrachloride (see Experimental Section for the composition of the starting materials) afforded a larger amount of 1-chloroadamantane and a smaller amount of 1-bromoadamantane. Controlled experiments showed that the product ratio (1-chloroadamantane to 1-bromoadamantane) increased with reaction time.[19] Similar reaction of 2-adamantanecarboxylic acid gave rise to 2-bromoadamantane and 2-chloroadamantane in a ratio of 1:0.11 and the ratio was practically constant during the reaction.

To obtain detailed information about the change of the ratio of bridgehead products, the reaction of 1-adamantanecarboxylic acid was followed at room temperature by successive withdrawal of the aliquots in a very early stage. The results are shown in Table III.

Table III. Product Ratio of the Modified Hunsdiecker Reaction of 1-Adamantanecarboxylic Acid[a]

Time, sec	1-Cl:1-Br
10	1.77
20	1.90
40	1.58
60	2.18
160	2.39
310	2.58
1800	4.60
7200	5.30

[a] Carboxylic acid (5 mmol), 5 mmol of red mercuric oxide, and 5 mmol of bromine in 25 ml of carbon tetrachloride at room temperature.

From extrapolation to time zero, a value of 1.68 was obtained as the inherent ratio of 1-chloroadamantane to 1-bromoadamantane.

The slow but steady increase in the ratio of 1-chloro- to 1-bromoadamantane can be taken as a result of some halogen exchange reactions (from bromine to chlorine) by some chloromercurial species accumulated during the reaction. The following observations are in accord with the mechanism. A certain carboxylic acid (acetic or cyclohexanecarboxylic acid[20]) was treated with red mercuric oxide and bromine in carbon tetrachloride. After the reaction was practically over (the bromine color disappeared), 1-bromoadamantane was added into the reaction mixture and was heated for several hours. 1-Bromoadamantane was completely converted to 1-chloroadamantane by the treatment. In the presence of mercuric chloride or silver chloride

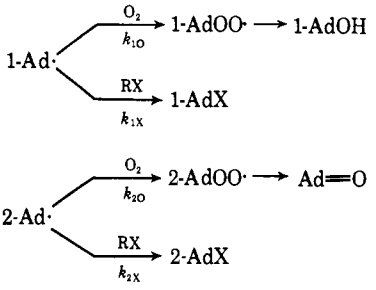
(14) D. D. Tanner and N. J. Bunce, *J. Amer. Chem. Soc.*, **91**, 3028 (1969), and references cited therein.
(15) The mechanism of the Hunsdiecker reaction of adamantanecarboxylic acid has turned out, by reexamination, to be not so simple as generally accepted. This point will be described and discussed later.
(16) Reference 1a, pp 287–295.
(17) G. W. Smith and H. D. Williams, *J. Org. Chem.*, **26**, 2207 (1961).
(18) S. J. Cristol and W. C. Firth, Jr., *ibid.*, **26**, 280 (1961).
(19) The reported results[10] of our preliminary examination of the Hunsdiecker reactions of 1- and 2-adamantanecarboxylic acids were the product compositions after halogen exchange reactions had taken place appreciably.
(20) The brominative decarboxylation of silver acetate: W. Bockemuller and W. Hoffmann, *Justus Liebigs Ann. Chem.*, **519**, 165 (1935). The brominative decarboxylation of silver cyclohexanecarboxylate: J. D. Roberts and U. C. Chambers, *J. Amer. Chem. Soc.*, **73**, 3176 (1951).

at 60° in carbon tetrachloride, 1-bromoadamantane was again completely converted to 1-chloroadamantane. Under similar condition, conversion of 2-bromoadamantane to 2-chloroadamantane was very slow.

Although it is apparent from these results that the first rapid Hunsdiecker reaction is followed by the second reaction of halogen exchange, it can be concluded that 1-adamantyl radical is less selective compared with 2-adamantyl radical by assuming that the Hunsdiecker reaction proceeds *via* a free-radical mechanism.

Discussion

Relative Lifetimes of 1- and 2-Adamantyl Radicals. The most important finding of the present study seems that only 1-adamantyl was captured by oxygen. In halogenation under oxygen, the fate of the adamantyl radical would be determined by four factors: k_{iO} (i = 1 or 2) (the rate constant of the capture of the i-adamantyl by oxygen), k_{iX} (i = 1 or 2) (the rate constant of the halogen atom abstraction by the i-adamantyl from a halogenating reagent), the concentration of oxygen, and the concentration of a halogenating reagent (RX).



Using the usual rate equation one may obtain an equation for the amounts of products expressed by rate constants in early stages of the reaction.

$$\frac{[\text{1-AdOH}]}{[\text{1-AdX}]} \Big/ \frac{[\text{Ad=O}]}{[\text{2-AdX}]} = \frac{k_{1O}[O_2]}{k_{1X}[RX]} \Big/ \frac{k_{2O}[O_2]}{k_{2X}[RX]} = \frac{k_{1O}}{k_{2O}} \frac{k_{2X}}{k_{1X}} \qquad (1)$$

Taking the nearly zero activation energy of the reaction of a carbon radical with molecular oxygen[21] into consideration, it would be safely assumed that almost every collision between the adamantyl radical and oxygen would result in the introduction of an oxygen function into adamantane. This means that k_{iO} values are much less sensitive to the structure of the parent radical than k_{iX} values are. If it is to be assumed that the rate constant of capture of 1-adamantyl by oxygen (k_{1O}) is approximately the same as that of 2-adamantyl (k_{2O}), eq 1 can be converted to a simpler form. The reciprocal of the rate constant for disappearance of a radical in solution is related to its lifetime; thus the expression using lifetimes (τ) of 1- and 2-adamantyl is also possible since γ_{obsd} was much larger than unity. k_{2X} should be much larger than k_{1X}. Calculation

$$\gamma_{obsd} = \frac{[\text{1-AdOH}]_{obsd}}{[\text{1-AdX}]_{obsd}} \Big/ \frac{[\text{Ad=O}]_{obsd}}{[\text{2-AdX}]_{obsd}} = \frac{k_{2X}}{k_{1X}} = \frac{\tau_1}{\tau_2} \qquad (2)^{22}$$

shows that the ratio of k_{2X} to k_{1X} in the case of NBS bromination is greater than 62.3 (corresponding activation free-energy difference for the bromine abstraction by 1-adamantyl and 2-adamantyl is greater than 3.0 kcal mol^{-1}) on the basis of eq 2 if the upper limit of the amount of adamantanone is assumed to be 1% of the amount of 1-adamantanol.[23]

Qualitatively, at least in the solvent investigated, 1-adamantyl is long-lived enough to allow competition between oxygen capture and halogen transfer reactions. On the contrary, 2-adamantyl is short-lived and it only abstracts the halogen atom from neighboring halogenated molecules before it diffuses away to meet with oxygen.

An important conclusion is that 1-adamantyl is formed easily and has a longer lifetime, suggesting that it may be considerably more stable than 2-adamantyl in the present condition (*vide infra*).

Indiscriminate Behavior of 1-Adamantyl under Competitive Bromination–Chlorination. It is demonstrated from the present observation that 1-adamantyl does abstract chlorine from bromotrichloromethane, while 2-adamantyl does not appreciably under the present conditions. A possible source of the present less selective distribution of bridgehead products might be some secondary reaction of halogen exchange, *i.e.*, the product, 1-bromoadamantane, might undergo reabstraction of bromine atom, giving again 1-adamantyl radical, which in turn abstracts chlorine as well as bromine, thus making the overall distribution less selective. However, reabstraction of the bromine atom from 1-bromoadamantane is concluded to be a very minor process, if not a negligible one, from the following observations. The BPO-initiated reaction of 1-bromoadamantane in carbon tetrachloride afforded 1-chloroadamantane and 1-bromo-3-chloroadamantane in a ratio of 28:72. Therefore, the bromine abstraction from 1-bromoadamantane is not so significant considering that no detectable amount of dihalogenated adamantanes was formed from adamantane in every monohalogenation run and that the product distribution was practically independent of reaction time in a very early stage of the reaction.

Rüchardt, *et al.*, recently studied[13] the product distribution of the decomposition of *tert*-butyl 1-adamantaneperoxycarboxylate in bromotrichloromethane–carbon tetrachloride and obtained a fairly indiscriminate bromide–chloride distribution compared with normal (discriminate) primary, secondary, and some bridgehead radicals other than 1-adamantyl.

Similar indiscriminate behavior of 1-adamantyl was also found in the Hunsdiecker reaction of 1-adamantanecarboxylic acid in carbon tetrachloride, where the ratio of 1-bromoadamantane to 1-chloroadamantane formed by inherent radical reaction was 1:1.68 if the ratio was extrapolated to time zero, while from 2-adamantanecarboxylic acid was obtained the corresponding 2-bromoadamantane and 2-chloroadamantane in a ratio of 1:0.11. If these ratios are taken as the selectivities of 1-adamantyl and 2-adamantyl in competitive bromination–chlorination, a somewhat

(21) Reference 1a, p 294.

(22) τ_1 and τ_2 are lifetimes of 1- and 2-adamantyl in solution, respectively, when the halogen abstraction is the only fate of radicals (*i.e.*, in the absence of oxygen).

(23) The yield of adamantanone was too low to allow its precise determination.

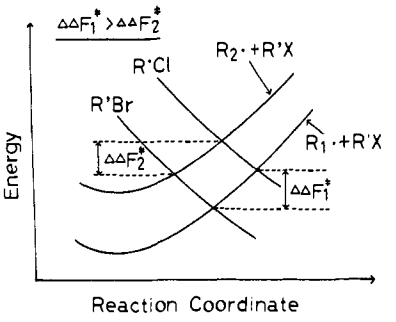


Figure 1. Reactivity–selectivity for similar radicals.

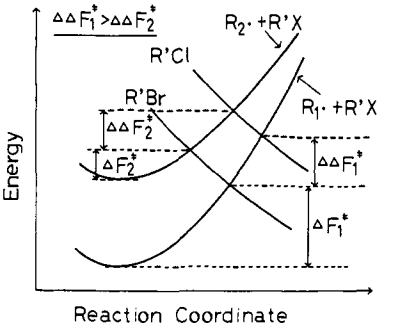
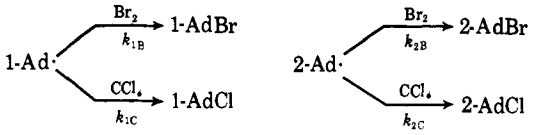


Figure 2. Reactivity–selectivity for unlike radicals (case a).

quantitative description for the indiscriminate behavior of 1-adamantyl may be possible. By the method



$$\frac{(k_{2B}/k_{2C})}{(k_{1B}/k_{1C})} = \frac{(1/0.11)}{(1/1.68)} = 15.3 \qquad (3)$$

$$\Delta\Delta\Delta F^{\ddagger} = \Delta\Delta F_2{}^{\ddagger} - \Delta\Delta F_1{}^{\ddagger} = (\Delta F_{2C}{}^{\ddagger} - \Delta F_{2B}{}^{\ddagger}) - (\Delta F_{1C}{}^{\ddagger} - \Delta F_{1B}{}^{\ddagger}) = 1.6 \text{ kcal mol}^{-1} \qquad (4)$$

analogous to that described above, it may be calculated that 1-adamantyl is more indiscriminate than 2-adamantyl by *ca.* 1.6 kcal mol^{-1} as to competitive bromination–chlorination.

Plausible Energy Diagram. Three important observations made in the present study are that 1-adamantyl (a) is more readily formed, (b) has a longer lifetime, and (c) is less selective in the halogen abstraction than 2-adamantyl. Here we have a serious deviation from the reactivity–selectivity relationship,[24] since the more stable 1-adamantyl behaves less selectively than less stable 2-adamantyl.[24] In Figure 1, the schematic representation of the well-known reactivity–selectivity relationship is given for the halogen transfer step where the two potential curves for $R_1\cdot$ and $R_2\cdot$ are similar (parallel). If the two potential curves are not parallel,[25] the arguments are not so straightforward. In case a (Figure 2), we still have the same conclusion about the reactivity–selectivity relationship. In case b (Figure 3), however, we have another possibility that the more stable radical reacts less selectively. This is presumably the case for 1-adamantyl and 2-adamantyl.

Thus, it may be concluded that the potential curve of the reaction of 2-adamantyl is remarkably steeper than that of 1-adamantyl. Different sensitivities of the potential curves of the reactions of 1- and 2-adamantyl to the reaction coordinate may best be understood on steric grounds.[26] In the case of 2-adamantyl, nonbonded repulsion between the radical

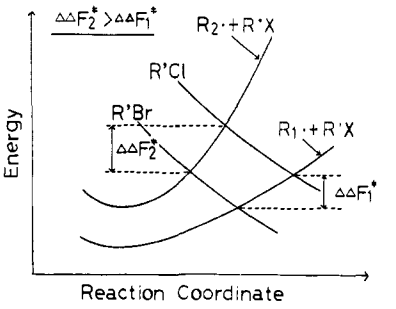


Figure 3. Reactivity–selectivity for unlike radicals (case b).

and a transfer reagent must be very significant because of β-axial hydrogens, raising the energy of the system more sensitively to the progress of the reaction (leading to a steep potential curve).

Thus, energy requirements for case b are satisfied. The only question remaining is: if the steric factor is concerned, why does not the difference in bulkiness of bromine and chlorine cause the change in the selectivity to favor the chlorine transfer than bromine from bromotrichloromethane?[27] Since the nonbonded repulsion does not differ much for chlorine and bromine[28] as well as for the trichloromethyl and bromodichloromethyl groups, the difference in bond energies seems to control the bromide:chloride ratio. The authors also investigated the bromide:chloride ratio in the addition of bromotrichloromethane to norbornene.[29] The predominant bromide formation observed (bromide:chloride to be 40 or more) supported the hypothesis.

In the hydrogen abstraction from adamantane, a steric control was also important (Table IV). Thus, with bromine or chlorine as abstracting species, the bridgehead attack (less crowded) is favored over bridge attack (more crowded) by a factor of only 3–5, while with the bulky trichloromethyl radical, the factor is around 25.

(24) Similar difficulties have been met in the case of 1-bicyclo[2.2.2]-octyl,[4,6,8] or more conspicuously in the fact that no real correlation can be obtained between the rates of the thermolysis of a series of *tert*-butyl peresters and product (brominated and chlorinated) distributions.[13] Reasonable explanations, however, have not been made anywhere.

(25) Some specific interactions may cause the deviation of the potential curve from the bond dissociation potential curve. Some destabilizing effects, such as nonbonded repulsion, may lead to a steeper potential curve because of additional energies, while some stabilizing effects, such as polar contribution, may lead to a milder potential curve.

(26) An alternative explanation may be made on the basis of the difference in polar contribution.[25]

(27) The question was posed by a referee.

(28) There is no significant difference between the conformational free energy of chlorocyclohexane and bromocyclohexane: E. L. Eliel, "Stereochemistry of Carbon Compounds," McGraw-Hill, New York, N. Y., 1962, Chapter 8.

(29) Exclusive formation of 2-*exo*-trichloromethyl-3-*endo*-bromonorbornane from bromotrichloromethane and norbornene was reported: E. Tobler and D. J. Foster, *J. Org. Chem.*, 29, 2839 (1964). Predominant formation of the endo chloride (endo:exo is 73:4) from carbon tetrachloride and norbornene was also observed: O. L. Osborn, T. V. van Auken, and D. J. Trecker, *J. Amer. Chem. Soc.*, 90, 5806 (1968). In both cases, the halogen transfer from the endo direction, due to a bulky trichloromethyl substituent present at the exo position, affords models of more hindered approach than 2-adamantyl.

Table IV. Bridgehead to Bridge Reactivity Ratios in the Free-Radical Substitution on Adamantane

Reagent (Abstracting species)	NBS (Br·)	NCS (Cl· and/or ·N(COCH$_2$)$_2$)	$Cl_2 + h\nu$ (Cl·)	($COCl_2$) (Cl·)	CCl_4 (CCl_3·)	$BrCCl_3$ (CCl_3·)
Reactivity ratio	2.5	2.5–3.7	1.9–6.3	3.7	24.3	27.0
Ref	*a*	*b*	*c*	*d*	*a*	*a*

[a] This work. [b] Reference 10. [c] Reference 17. [d] I. Tabushi, J. Hamuro, and R. Oda, *J. Org. Chem.*, **33**, 2108 (1968).

From these considerations is obtained a plausible energy diagram of the free-radical halogenation on adamantane which is shown in Figure 4.

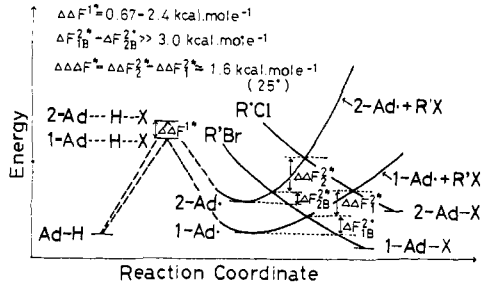


Figure 4. Energy diagram of the free-radical halogenation on adamantane (unless otherwise noted, values at 95° are shown).

Experimental Section

Materials and Analyses. Commercially available adamantane (Aldrich) was used for the substrate. 1-Adamantanecarboxylic acid was prepared by the Koch–Haaf carboxylation.[30] 2-Adamantanecarboxylic acid was obtained by the chlorocarbonylation of adamantane.[31] Except adamantanone (Aldrich), all other monosubstituted adamantanes were prepared by the published procedures.[32] Nitrogen gas was passed through an alkaline solution of pyrogallol and a calcium chloride tube. Hydrogen bromide was generated by the action of bromine on red phosphorus in water and was dried.

Identification of products was made by means of gas–liquid partition chromatography (glpc) coinjection with authentic samples, using two kinds of columns (PEG 20M, 2.5 m, and Silicone SE-30, 2.5 m, 170°). When necessary, the product was isolated by preparative glpc and its ir, mass, and/or nmr spectra were compared with those of the authentic sample to ascertain its structure (especially in the case of 1-chloroadamantane from the reaction of adamantane with bromotrichloromethane). Analyses were made on crude reaction mixtures by means of glpc and different sensitivities of the products to glpc peak area were calibrated with authentic samples. Relative molar sensitivities of 1-adamantanol, 1-chloroadmantane, and 1-bromoadamantane were found to be 1, 1.17, and 1.42, respectively, and identical sensitivities were assumed for the isomers.

Substitution on Adamantane. As a typical example, NBS bromination under nitrogen is described in some detail. Procedures for the substitutions using other reagents were similar. In a 50-ml flask equipped with a reflux condenser and a gas inlet tube were placed 2 g of adamantane, 0.67 g of NBS, 45 mg of BPO, and 30 g of chlorobenzene. Nitrogen gas was introduced and the mixture was heated at 95°. Every 1 hr the mixture was analyzed by glpc and an additional 45 mg of BPO was added until the total conversion reached 17%.

NBS bromination under hydrogen bromide or in the presence of sodium carbonate (10 g of sodium carbonate per gram of adamantane) was carried out similarly.

The procedure was essentially the same for the substitution in an oxygen atmosphere except that much care was taken to keep the flow of oxygen constant for all runs. A solution of 1 g of adamantane and 50 mg (in two portions) of BPO in 30 ml of carbon tetrachloride was heated at 95° under a constant flow of oxygen for 2 hr. The carbon tetrachloride was removed *in vacuo* and the residue was dissolved in dry ether. The ether solution was added to a solution of excess lithium aluminum hydride in dry ether at room temperature. The mixture was stirred for 1 hr and then poured on crushed ice and extracted. Glpc analyses were made both on samples before and after lithium aluminum hydride treatment and it was shown that lithium aluminum hydride treatment brought about no appreciable change in the product composition (no 2-oxygenated adamantanes were detected in the latter case).

Reaction of 1-Bromoadamantane with Carbon Tetrachloride. A solution of 500 mg of 1-bromoadamantane and a small amount of BPO in 30 ml of carbon tetrachloride was heated at 95° under nitrogen for 3 hr. Glpc analysis showed two products other than the recovered bromide. They were separated by means of preparative glpc. Of these, one was identified as 1-chloroadamantane. Its ir spectrum was identical with that of the authentic sample. The other product was identified as 1-bromo-3-chloroadamantane on the basis of spectroscopic evidence and glpc coinjection with the authentic sample. Authentic 1-bromo-3-chloroadamantane was prepared by free-radical bromination of 1-chloroadamantane. Thus a solution of 1.9 g of 1-chloroadamantane and 300 mg (in three portions) of BPO in 10 ml of bromotrichloromethane was heated at 90° for 20 hr. After cooling, most of the bromotrichloromethane was removed *in vacuo* and the residue was chromatographed on a silica gel column (petroleum ether). After elution of the starting material, crude 1-bromo-3-chloroadamantane was eluted (*ca.* 800 mg). The pure compound was obtained by repeated recrystallization from petroleum ether: mp 99–100° (uncorrected); nmr ($CDCl_3$, TMS) τ 7.33 (2 H), 7.72 (6 H), 7.87 (4 H), 8.33 (2 H); ir (KBr) 1290, 1023, 817, 754, and 705 cm^{-1}; mass spectrum, *m/e* 252 (relative intensity 0.3), 250 (1.3), 248 (1.0), 215 (3.1), 213 (3.4), 171 (32), and 169 (100).

Anal. Calcd for $C_{10}H_{14}BrCl$: C, 48.12; H, 5.65. Found: C, 48.40; H, 5.86.

Hunsdiecker Reactions of Adamantanecarboxylic Acids. A mixture of 0.9 g (5 mmol) of 1-adamantanecarboxylic acid, 1.1 g (5 mmol) of red mercuric oxide, and 20 ml of carbon tetrachloride was stirred at room temperature for 2 hr. Into the mixture was added very rapidly (during *ca.* 1 sec) 0.8 g (5 mmol) of bromine in 5 ml of carbon tetrachloride. At an appropriate time interval, an aliquot was withdrawn and poured into 20% aqueous sodium hydroxide or concentrated hydrochloric acid. After the addition of a small amount of carbon tetrachloride, the organic layer was analyzed. The reaction of 2-adamantanecarboxylic acid was carried out similarly.

To eliminate any difference in the experimental conditions for the separate reactions of 1- and 2-adamantanecarboxylic acids, the mixture of two isomeric acids was also used for the reaction. The reaction was followed by taking out aliquots at appropriate intervals of time to investigate the ratio of chloride to bromide at both 1 and 2 positions. The ratio was extrapolated to time zero to give the inherent chloride to bromide ratio.

Halogen Exchange in Hunsdiecker Mixture. A mixture of 1 g (8 mmol) of cyclohexanecarboxylic acid and 1.7 g (8 mmol) of red mercuric oxide in *ca.* 20 ml of carbon tetrachloride was stirred at 60° for several minutes, then 1.3 g (8 mmol) of bromine was added very rapidly. On stirring the mixture for a few minutes, the color of bromine disappeared; then 0.6 g (2.8 mmol) of 1-bromoadamantane was added. The reaction mixture was heated at 60° for 2 hr. On cooling to room temperature, inorganic materials were filtered off and the filtrate was analyzed. It was found that 1-bromoadamantane had been almost completely converted to 1-chloroadamantane (68%), another main product being cyclohexyl bromide (40%). Use of acetic acid instead of cyclohexanecarboxylic acid

(30) H. Koch and W. Haaf, *Org. Syn.*, **44**, 1 (1964).
(31) Footnote *d* in Table IV.
(32) 1-Bromo-, 1-chloro-, 1-hydroxy-, and 2-hydroxyadamantane: R. C. Fort, Jr., and P. von R. Schleyer, *Chem. Rev.*, 277 (1964), and references cited therein. 2-Bromo- and 2-chloroadamantane: W. Hoek, J. Strating, and H. Wynberg, *Recl. Trav. Chim. Pays-Bas.*, **85**, 1045 (1966).

lowered the conversion of 1-bromoadamantane to 1-chloroadamantane.

Halogen Exchange with Mercuric Chloride. A mixture of 29 mg (0.133 mmol) of 1-bromoadamantane and 43 mg (0.2 mmol) of mercuric chloride in 20 ml of carbon tetrachloride was heated at 60° for 3 hr in a sealed tube. The usual work-up and analysis showed that the yield of 1-chloroadamantane was 95%. When silver chloride was used in place of mercuric chloride, the conversion of 1-bromoadamantane to 1-chloroadamantane was somewhat lowered.

Zwitter Annihilation in the Halogenation of Allylic Alkoxides. The Δ^8-1-Phenyl-1-octalol System[1]

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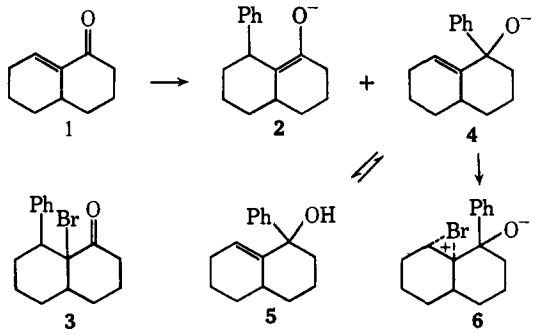
Contribution from the Department of Chemistry, Rutgers University, Newark, New Jersey 07102. *Received April 23, 1971*

Abstract: Treatment of the magnesium bromide salt of Δ^8-1-phenyl-1-octalol (**4a**) with bromine leads to two rearranged β-bromo ketones **10b** and **11b**, whose carbon skeletons and stereochemistry have been established by independent syntheses. It is shown that for at least one of the products, rearrangement results from collapse of a bromonium alkoxide intermediate in the halogenation. This interpretation is discussed in terms of related rearrangement mechanisms and homoenolate structures.

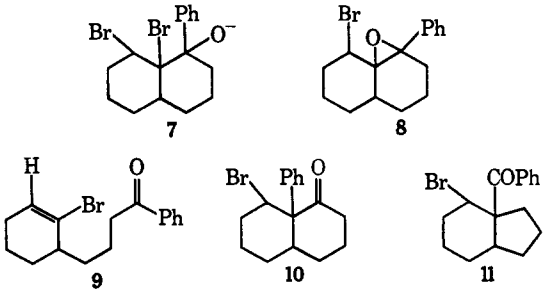
In the course of other synthetic work we required a method for preparing bromo ketone **3**, and consequently attempted direct halogenation of the magnesium enolate **2**, obtained by conjugate addition of phenyl Grignard to Δ^8-1-octalone (**1**).[3] We isolated, in addition to an α-bromo ketone,[3] an isomeric monobromo ketone, mp 110–112.5°,[3] whose spectral and chemical properties, however, could not all be reconciled with a structure bearing the halogen at a position α to the carbonyl group.[4,5]

Scheme I



At this juncture, we perceived that bromination of the "normal" Grignard product known to be present in the mixture,[3] a tertiary allylic alkoxide **4**, might, by internal neutralization of the intermediate **6**, give rise to ketonic products bearing bromine at sites more remote from the carbonyl group than we had originally anticipated.

This presumed intermediate in the bromination of **4**, the bromonium alkoxide **6**, could theoretically undergo a variety of reactions. The simplest of these would be attack by bromide ion to give a dibromo alkoxide (**7**), or direct internal attack of the alkoxide at either the more positive or more accessible of the two carbon atoms involved in the bromonium ion, to give a bromo epoxide **8** (or an oxetane). If the zwitter annihilation were not to take place by direct attack of the alkoxide on the bromonium ion, the presence of a tetrahedral carbon between the positively and negatively charged centers would require migration of one of the tetrahedral bonds to allow neutralization. Three different simple rearrangment products are possible, **9**–**11**, each corresponding to migration of one of the bonds at the alkoxide carbon.



Of the three possible ketonic products, only **10** fits the infrared spectral data for our compound. The tentative conclusion that our bromo ketone was **10**, which arose from **4** present during the bromination, was therefore tested by bromination of the pure allylic alkoxide **4** and independent synthesis of the carbon skeleton of **10**. A sample of the isolated and purified tertiary alcohol **5**[3] was reconverted with phenylmagnesium bromide to its salt, **4**, and brominated. Work-up by addition of basic, saturated aqueous ammonium chloride, followed by chromatography, provided the same bromo ketone **10** in 36.5% yield.

For several reasons involving steric and electronic factors in **1**, the stereochemistry of **4** is believed to be that shown in **4a** (Scheme II).[3,6] This stereochemistry

(1) Abstracted in part from the Ph.D. Thesis of R. R. M.
(2) National Institutes of Health Predoctoral Fellow, 1970–1971.
(3) H. O. House and H. W. Thompson, *J. Org. Chem.*, **28**, 360 (1963).
(4) L. F. Fieser and M. Fieser, "Steroids," Reinhold, New York, N. Y., 1959, pp 170, 282–284.
(5) (a) A. Nickon, M. A. Castle, R. Harada, C. E. Berkoff, and R. O. Williams, *J. Amer. Chem. Soc.*, **85**, 2185 (1963); (b) A. Baretta, J. P. Zahra, B. Waegell, and C. W. Jefford, *Tetrahedron* **26**, 15 (1970).
(6) E. Toromanoff, *Top. Stereochem.*, **2**, 187 (1967).