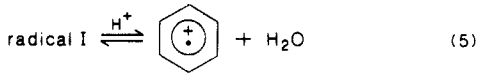
radical I is rapidly converted to peroxy radical (radical II), which according to Dorfman[3] also produces phenol by releasing an HO_2 radical. These mechanisms seem applicable without any modification to the formation of phenol in the Cu^+/O_2 system.

As for hydroquinone, its formation route was found to be competitive with that of phenol, and the isotope incorporation satisfied the simple probability rule so that the fraction of doubly labeled product was equal to the square of the fractional isotope content in the reacting gas. Undoubtedly, the first isotope is incorporated at the stage of radical I, and the second incorporation occurs at radical II. No peculiar mechanism inherent to the Cu^+/O_2 system is necessarily taken into account.

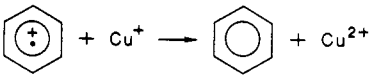
There is another point to be noted. According to Norman[18,19] and Walling,[4,5] a hydroxycyclohexadienyl radical (radical I), which is believed to be the primary intermediate in the reaction, suffers the acid-catalyzed dehydration reaction shown in eq 5. The dehydration step is thought



(5)

to be in quasi-equilibrium with the reverse hydration reaction. If the rate of the backward reaction is large enough, the isotope content in radical I should be lowered because the backward reaction produces nonlabeled radical I. Along this line, Vysotskaya[20] studied the ^{18}O incorporation in phenols produced during the Fenton reaction of some substituted benzenes and reported that the isotopes scrambling due to eq 5 was confirmed. Although we may be somewhat skeptical[21] about the accuracy of their experiment we still have no reason to deny their result.

The data in Table I, however, do not show such a scrambling effect. We are left with the question why the scrambling takes place in the Fenton system but not in the Cu^+ system. A tentative but consistent explanation for this apparent contradiction may be obtained if we assume a rapid electron transfer between the cation radicals produced by eq 5 and Cu^+ ions (eq 6).



(6)

A similar reaction with Fe^{2+} ions in place of Cu^+ was originally proposed by Walling.[4,5] The electron-transfer reaction may be faster with Cu^+ than Fe^{2+} ions so that the reverse reaction back to radical I can safely be ignored and the isotope concentration in phenol will become equal to that of the reacting gas. If this is true, it may also be true that some of the Cu^+ ions and thus radical I are wasted by this mechanism. This may be an answer to the question why the efficiency is lower with Cu^+ ions than Fe^{2+} ions, which was raised in the introduction of this paper. Unfortunately, however, we have not got any further information yet to give a certain answer to this problem.

In any case, we believe that almost all of the apparent differences found between the Cu^+/O_2 and Fe^{2+}/H_2O_2 systems can be attributed to the different redox behavior of the $Cu^{+/2+}$ and $Fe^{2+/3+}$ couples; i.e., while the Cu^+ reduction of O_2 is fast, Fe^{2+} reduction of O_2 is too slow to be important. This is the reason why hydrogen peroxide is necessary in the Fenton reaction. The reason why hydroquinone is produced appreciably in the present system but not in the Fenton system may also be related to the different redox behavior of the two metal ion couples, though the details are left for further study.

The absence of biphenyl in the present system should be ascribed to the effect of oxygen which rapidly converts radical I to II. Direct oxidation of radical I by Cu^{2+} ions may also be responsible for the absence of biphenyl.

Acknowledgment. A part of this paper was supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture (61470081).

Registry No. CuCl, 7758-89-6; benzene, 71-43-2.

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(20) Vysotskaya, N. A.; Shevchuk, L. G. *Zh. Org. Khim.* **1973**, *9*, 2080.
(21) The isotope levels used in their experiments seems too low to draw any accurate conclusion. In addition, according to their result at pH 1.5 (run 13 of their table), which was done at conditions more or less similar to our experiments,[8] 99% of phenol produced contain hydroxyl groups originated from water; i.e., 99% of phenol is formed by passing through the benzene cation radical. This is not only incredible in itself but also disagrees with our result described in the succeeding paper (See Table I, ref 8).

Effect of Dihydroaromatic Compounds on the Cation Radical Chain Oxygenation of Tetraalkyl Olefins

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Ionic chain hydrogenation of *syn*-sesquinorbornene (**7**) to **13** by 1,4-cyclohexadiene (**11**) may be initiated by tris(2,4-dibromophenyl)aminium ($9^{\bullet+}$) hexachloroantimonate at −78 °C and is efficient enough to inhibit cation radical catalyzed oxygenation of **7** by oxygen. The chain-carrying steps appear not to involve radicals, and the reaction can be initiated by HBF_4 at low temperature or TFA at above room temperature. *anti*-Sesquinorbornene (**8**) is considerably less reactive and requires HBF_4 to initiate hydrogenation. Isopropylideneadamantane (**16**) requires FSO_3H for initiation, but biadamantylidene (**1**) is not hydrogenated under our conditions. Nevertheless, addition of 5 equiv of **11** intercepts the kinetic chain for cation radical catalyzed oxygenation of **1** to dioxetane **2**; the chain length for consumption of **1** drops from over 800 to less than 2, and epoxide **19** becomes a major product. It is proposed that the open peroxy carbocation $B^{\bullet+}$ is trapped by **11** to lead to the observed results.

Tetraalkyl olefins containing α-branched alkyl groups which hold their C_α–H bonds near the nodal plane of the olefin π system, such as biadamantylidene (**1**), give unusually kinetically stable cation radicals,[1] making their

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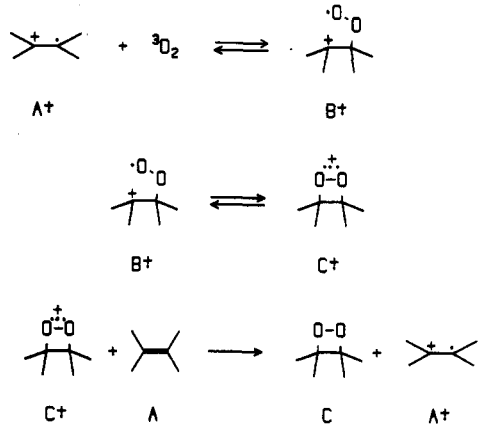
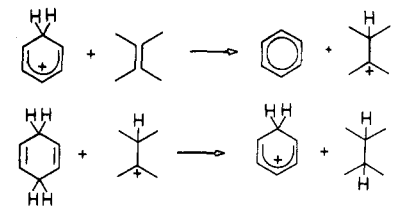
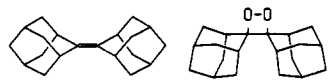
Scheme I



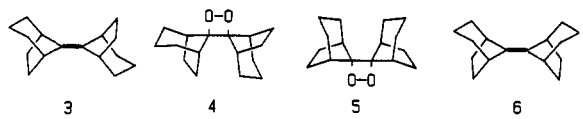
Scheme II



reactions easier to study than those of "unprotected" olefins. $1^{\bullet+}$ initiates a cation radical chain reaction[2] in



which triplet oxygen adds to **1** to give the dioxetane **2**, with a chain length (moles of **2** produced per mole of $1^{\bullet+}$ employed) of over 800 at −78 °C.[3] **1** and its analogues which undergo radical cation chain oxygenation to dioxetanes show characteristic EC backward E (ECbE) wave shapes in their cyclic voltammetry (CV) curves,[2a,b] which is consistent with oxygenation of $1^{\bullet+}$ producing a stronger oxidant than $1^{\bullet+}$ when it reacts with oxygen. ESR and CV studies of **1** have shown that $2^{\bullet+}$ is the probable precursor of **2**[4] and that $2^{\bullet+}$ loses oxygen to give $1^{\bullet+}$ at room temperature.[5] Product studies on the oxygenation of *anti*-bi-8-bicyclo[3.2.1]octylidene (**3**) have established that rotation about the central bond after addition of O_2 to $3^{\bullet+}$ is competitive with formation of dioxetane **4**, because dioxetane **5**, the sole product from the syn olefin **6**, is a minor product from **3** under conditions where $3^{\bullet+}$ and $6^{\bullet+}$ do not interconvert.[6] These results led us to suggest the

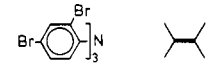


three step chain propagation shown in Scheme I for these reactions. $B^{\bullet+}$ has not been directly detected; if present in significant amounts in solutions of $1^{\bullet+}$ and **1** reacting with O_2, it is electroinactive in the potential region 1.3–2.3 V vs. SCE and does not show an ESR spectrum under conditions where $2^{\bullet+}$ is observed.[4] This work reports experiments in which dihydroaromatic compounds were added to the oxidation reaction mixtures to try to intercept $B^{\bullet+}$ in the cation radical chain oxidation of tetraalkyl olefins by hydrogen atom or hydride abstraction.

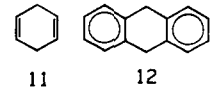
Results: Ionic Chain Hydrogenation of Sesquinorbornenes

Despite the fact that *syn*- and *anti*-sesquinorbornenes (**7**[8] and **8**[9]) give cation radicals that are long-lived on the CV time scale (seconds) at room temperature and that last for minutes at −78 °C, their reactions with oxygen show very different characteristics from those of **1** and several other tetraalkyl olefins.[5,7] Although the oxidation wave

in an oxygen atmosphere becomes totally irreversible, showing that the cation radicals react rapidly with oxygen, and the oxidation current is decreased, the characteristic ECbE wave shape is not observed. Their cation radicals do not react with oxygen to produce an oxidant capable of oxidizing the olefins rapidly, suggesting that the dioxetane cation radicals are not formed. Experiments using the chemical oxidant tris(2,4-dibromophenyl)aminium hexachloroantimonate ($9^{\bullet+}$), the oxidant of choice for initiation of tetraalkyl olefin oxygenations,[3] show that long chain oxygenation reactions are not initiated. Instead, oxygenated products which have not yet been characterized are produced by reactions which require approximately stoichiometric amounts of $9^{\bullet+}$ for complete consumption of olefin. This behavior qualitatively resembles



that of 2,3-dimethylbutene (**10**) and other tetraalkyl olefins which lack α-branched carbons.[7] Because **7** and **8** react with oxygen but apparently do not produce dioxetane cation radicals $C^{\bullet+}$, we hypothesized that closure of $B^{\bullet+}$ to $C^{\bullet+}$ might be slower for these compounds than for ones which give dioxetanes; the closed cations are obviously strained by the bicyclic rings. We therefore thought that these cases might be unusually good ones for trapping the presumed initial oxygen adduct $B^{\bullet+}$, which was attempted with 1,4-cyclohexadiene (**11**) and 9,10-dihydroanthracene (**12**). Although these attempted trapping reactions failed completely, they led to the discovery that **7** and **8** are excellent substrates for ionic chain hydrogenation reactions, and we will describe the experiments here.



(1) Nelsen, S. F.; Kessel, C. R. *J. Am. Chem. Soc.* **1979**, *101*, 2503.
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(3) Nelsen, S. F.; Kapp, D. L.; Teasley, M. F. *J. Org. Chem.* **1984**, *49*, 579.
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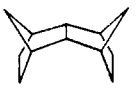
Table I. Summary of Ionic Hydrogenation Reactions of Sesquinorbornenes

temp, °C	olefin (M)	reductant (equiv)	initiator (mol %)	result
−78	7 (0.06)	11 (10)	23% $9^{\bullet+}$ [a]	63% 13 isolated
−78	7 (0.13)	11 (10)	30% $9^{\bullet+}$	79% 13 isolated
−78	7 (0.06)	11 (10)	5% $9^{\bullet+}$	54% 13, 46% 7; CL = 11
−78	7 (0.06)	11 (10)	20% TFA	90% 7, 10% 14
−78	7 (0.025)	12 (5)	10% $9^{\bullet+}$	89% 13 isolated
−78	7 (0.025)	12 (5)	1% $9^{\bullet+}$	35% 13, 65% 7; CL = 35
−78	7 (0.09)	11 (5)	10% $9^{\bullet+}$	13–benzene (1:1)
−78	7 (0.09)	11 (5)	5% HBF_4	13–benzene (1:1)
+40	7 (0.09)	11 (5)	excess TFA	79% 13 isolated
−78	8 (0.06)	12 (5)	1.4% $9^{\bullet+}$	no reduction
+25	8 (0.06)	11 (5)	5% HBF_4	15–benzene (1:1)
+25	8 (0.06)	11 (5)	10% HBF_4	79% 15 isolated

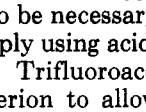
[a] Reaction run saturated with O_2; all others under N_2.

Oxygenation of *syn*-sesquinorbornene (**7**) by oxygen in the presence of $9^{\bullet+}$ is inhibited by 1,4-cyclohexadiene (**11**); the observed products were hydrogenation product **13** and benzene. Although **7** is too hindered to be hydrogenated



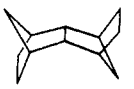
13

to **13** over transition-metal catalysts, it is efficiently reduced by reaction of **7** with diimide.[10] Benzene is produced in equal amount to **13**, and the reaction is catalytic in $9^{\bullet+}$. Use of 5 mol % $9^{\bullet+}$ with a 10-fold excess of **11** gave 54% **13** and 46% recovered **7**, corresponding to a chain length of 11. Reduction proved to be somewhat more efficient using 9,10-dihydroanthracene (**12**) as reductant, as a chain length of about 35 was found. In the preparative run using **12**, an equivalent of anthracene was formed along with **13**, as observed by ^1H NMR. These experiments are summarized in Table I. Although the hydrogenations observed might well have been initiated by $9^{\bullet+}$ under the conditions used, hydrogen atom transfer from **11** to $7^{\bullet+}$ would generate cyclohexadienyl radical, which would be rapidly oxidized to protonated benzene under the reaction conditions. Protonated benzene would be expected to participate in a catalytic ionic hydrogenation reaction,[11] as outlined in Scheme II. This suggested that one electron oxidation ought not to be necessary to initiate reduction of **7** by **11** and **12**; simply using acid should suffice, which proved to be the case. Trifluoroacetate proved to be too nucleophilic a counterion to allow trifluoroacetic acid (TFA) to initiate the reaction at low temperature, and it simply adds to **7** even in the presence of **11** at −78 °C, followed by warming to room temperature. A 1.25 M solution of **7** in CD_2Cl_2 treated with 1 mol equiv of TFA gave a 95:5 mixture of the trifluoroacetate **14**:**7**, and addition of excess TFA followed by addition of excess K_2CO_3 to neutralize the acid gave a filtrate containing a 58:42 mixture, indicating that the addition is reversible at room temperature. Refluxing a mixture of **7**, **11**, and TFA did give **13**; such conditions are similar to those of typical ionic hydrogenations, in which trialkylsilanes are used as the hydrogen donor.[11] One possible advantage of using dihydroaromatics as the reductant is that stronger acids could be employed; trialkylsilanes do not survive treatment with acids much stronger than TFA. Treatment of **7** and **11** in CD_2Cl_2 at −78 °C with 5 mol % HBF_4–Et_2O did give a 1:1 mixture of **13** and benzene.



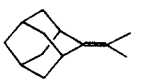
14

anti-Sesquinorbornene (**8**) was found to be less reactive than the syn isomer **7** in ionic hydrogenation reactions. We observed no reaction at −78 °C with either aminium salt $9^{\bullet+}$ or HBF_4–Et_2O as catalysts, but the acid-catalyzed reaction did proceed at room temperature in several hours. A 79% yield of **15** was isolated by chromatography in a preparative run. The ionic hydrogenation reactions are summarized in Table I.



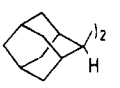
15

We conducted a brief survey which showed that the unusual reactivity of sesquinorbornenes in addition reactions[8,9] is important in causing reduction to occur under the conditions we used in Table I. Isopropylideneadamantane (**16**) is far more sluggish to reduce, and neither $9^{\bullet+}$ nor HBF_4–Et_2O gave any reduced product. When a



16

0.08 M solution of **16** in CD_2Cl_2 containing 5 equiv of **11** was cooled to −78 °C, treated with 30 mol % of the stronger acid FSO_3H, and warmed to room temperature, a 99% yield of the reduction product 2-isopropyladamantane was isolated by chromatography. We found ourselves, however, completely unable to reduce biadamantylidene (**1**), even with FSO_3H as catalyst; it is presumably simply too hindered. A sample of the reduction product **17**[12] was prepared, and this compound was not detected in any of our reaction mixtures. Norbornadiene and norbornene con-



17

taining 5 equiv of **11** react rapidly with 5% HBF_4 at −78 °C to produce some benzene; so some reduction is occurring, but the major product is polymeric, and hydrogenation is not the major reaction under these conditions. Finally, both **10** and 1,2-dimethylcyclohexene (**18**) gave no benzene when mixtures with **11** were treated with FSO_3H at −78 °C and warmed to room temperature. Apparently

18

the extra stabilization of the 2-alkyl-2-adamantyl cation promotes protonation of **16** relative to the 2-alkyl-2-propyl cation from **10** so that for the former the hydrogenation will proceed. In general, the ease of ionic hydrogenation

(10) See ref 8c. We thank Professor Paquette for an authentic sample of **13**.

(11) For reviews of catalytic ionic hydrogenation, see: (a) Kursanov, D. N.; Parnes, Z. N.; Loim, N. M. *Synthesis* **1974**, 633. (b) Kalinkin, M. I.; Kolomnikova, G. D.; Parnes, Z. N.; Kursanov, D. N. *Russ. Chem. Rev.* (*Engl. Transl.*) **1979**, *48*, 332.

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Table II. Products from the Oxygenation of 1 in Oxygen-Saturated CH_2Cl_2 Containing 5 Mol Equiv of 11 or 12 at -78 °C.

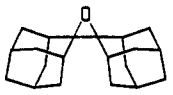
			products, %			
[1], mM	reductant	$9^{\bullet+}$	olefin 1	epoxide 19	dioxetane 2	CL[a]
37	11	50	43	36	21	1.1
37	11	70	5	40	55	1.4
37	11	80	7	58	35	1.2
37	11	100	5	72	23	1.0
12	12	50	70	27	3	0.6
9	12	100	38	48	14	0.6

[a] % (19 + 2)/%$9^{\bullet+}$.

of the α-branched olefins discussed should be controlled by the stability of the cations produced, since hydride transfer is the slow step and protonation should be facile under the reaction conditions.[11] Ionic chain reduction of olefins by dihydroaromatics under the conditions reported here is obviously not a very general reaction, but it does proceed fast enough for the unusually reactive 7 to stop oxygenation from competing with it.

Results and Discussion: Chemical Trapping of $B^{\bullet+}$ from 1

Chemical trapping of the $B^{\bullet+}$ adduct from 1 has been previously suggested. When $NO^+BF_4^-$ is used as oxidant for 1, in the presence of oxygen, epoxide 19 is a major product,[2a] and it was suggested that the NO formed when 1 was oxidized to $1^{\bullet+}$ might have added to the terminal oxygen of $B^{\bullet+}$ and the adduct might have cleaved to NO_2^+ and 19. Akaba and co-workers[13] have also reported



19

trapping of $B^{\bullet+}$, where irradiation of 1, tetracyanoethylene (TCNE), and oxygen gives 19 and the epoxide of TCNE. They suggest that addition of $B^{\bullet+}$ to $TCNE^{\bullet-}$ would give a zwitterion which should cleave to the observed products.

The experiments reported in the previous section show that 1,4-cyclohexadiene (11) does not give ionic hydrogenation of 1, so its use as a trap for $B^{\bullet+}$ can be considered. Qualitative cyclic voltammetry experiments indicated that some intermediate from the reaction of $1^{\bullet+}$ with oxygen was reacting with 11. 11 shows a broad, totally irreversible wave peaking about 2.3 V vs. SCE, which is positive enough that it does not interfere much with the $1,1^{\bullet+}$ wave, which is centered at 1.6 V. The CV curve for 1 at -78 °C is rather broad (the peak-to-peak width, $E_p^{ox}-E_p^{red}$, is not very reproducible and in the range 110–300 mV depending on the history of the electrode employed) but chemically reversible (the reduction wave is as large as the oxidation wave). Adding 5 equiv of 11 does not affect the chemical reversibility, so $1^{\bullet+}$ does not react with 11 on the CV time scale. When CV solutions containing 1 are saturated with oxygen, the characteristic ECbE wave shape is observed[5] (lower peak currect, faster drop off in current past the peak potential, and crossover of the reduction and oxidation scans at slow scan rates), but in the presence of 5 equiv of 11, the oxidation wave is totally irreversible but with a higher current than that under nitrogen. This suggests that some intermediate formed from $1^{\bullet+}$ and oxygen is being trapped by 11 before $2^{\bullet+}$ ($C^{\bullet+}$ when 1 is A) is formed and is consistent with the desired trapping of $B^{\bullet+}$.

Addition of 11 to the oxygenation reaction mixtures of 1 has a profound effect on the products formed. In the absence of 11, oxygenation of 1 at -78 °C gives 2 as the only product, with chain lengths on the order of 800–1000 when small amounts (ca. 0.1 mole %) of $9^{\bullet+}$ are used to initiate the chain reaction by exothermic generation of $1^{\bullet+}$ (Scheme I).[3] Under the same conditions but with 5 equiv of 11 present, 5 mol % $9^{\bullet+}$ only oxidizes trace of 1; both dioxetane 2 and epoxide 19 are formed. Experiments using 50–100 mol % $9^{\bullet+}$ were carried out so that enough conversion would occur to enable the products to be quantitated better, and the results appear in Table II. The long chains for oxygenation of 1 are completely inhibited, and 19 becomes a major product. The ratio of epoxide 19 to dioxetane 2 generally increases as the amount of oxidant increases, but control experiments indicate that 2 is converted to 19 under the reaction conditions. Treatment of 20 mM 2 in CH_2Cl_2 containing 100 mM 11 with 100 mol % $9^{\bullet+}$ under nitrogen at -78 °C for an hour gave only 33% recovered 2, 48% epoxide 19, and 19% adamantanone, and a repetition of this experiment under an oxygen atmosphere gave 19% recovered 2, 67% 19, and 14% adamantanone. The conditions of these experiments are different from those in Table II because electron transfer from 2 to $9^{\bullet+}$ is endothermic by 14 kcal/mol, rather than exothermic as seen for 1. With the working assumption that all 19 produced arises from trapping of $B^{\bullet+}$ by 11, it appears that the $B^{\bullet+}$ intermediate can be generated from either side, which in Scheme I means either $A^{\bullet+}$ or $C^{\bullet+}$. The fact that epoxide 19 could be detected even with only 5 mol % $9^{\bullet+}$ suggests that at least some of it is a primary product of the trapping sequence.

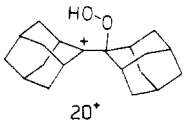
Despite the increasing ratio of 19 to 2 discussed above, the ratio of $9^{\bullet+}$ used to 19 produced stayed constant at about 1.4:1. Presumably, every $9^{\bullet+}$ ultimately gives rise to a $B^{\bullet+}$ which is trapped by 11, whether it catalyzes formation of 2 or not, so the constant ratio seen is noteworthy since it suggests that 11 is not the most efficient trap possible, as seen below.

The experiments with the more reactive reductant 9,10-dihydroanthracene (12) reported in Table II indicate that it is a more efficient trap than 11. The chain length is even shorter than with 11 because the yields of epoxide 19 and dioxetane 2 are lower, suggesting that their common precursor $B^{\bullet+}$ is trapped more efficiently. Because of the lower volatility of the aromatic, a stoichiometry of 2:1 for 9:anthracene could be established for both reactions after their completion when using 12 as reductant. Since the ratio of $9^{\bullet+}$ used to the 19 produced is also 2:1, this suggests that there is an approximately 1:1 correspondence for products 19 and anthracene. Thus it appears that the majority of the adduct produced by trapping of $B^{\bullet+}$ does gives rise to epoxide 19 as product as assumed earlier.

Our results show that the weak hydrogen atom or hydride donors 11 and 12 strongly inhibit the dioxetane-forming kinetic chain of Scheme I. It seems most unlikely to us that $2^{\bullet+}$ ($C^{\bullet+}$ of Scheme I) has significant hydrogen atom or hydride abstracting properties, which would require relinquishing the stabilization of the three-electron π bond; if it reacted, we would expect it to be reduced and

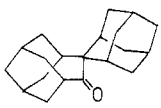
(13) Akaba, R.; Sakuragi, H.; Tokumaru, T. *Chem. Lett.* **1984**, 1677.

give dioxetane, and 1 is a far better one-electron donor than the dihydroaromatics. We suggest that the reason for the dihydroaromatics breaking the kinetic chain is that they trap the open peroxy carbocation $B^{\bullet+}$ by hydrogen atom donation, generating 20^+, or by hydride donation, giving $20^\bullet$, its one-electron reduction product. It is cer-

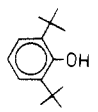


20^+

tainly not obvious to us what sequence of reactions would be involved in the conversion of 20^+ to the major observed product, epoxide 19, but $20^\bullet$ could very well give 19 by elimination of $HO^\bullet$. The work of Akaba, Sakuragi, and Tokumaru[14] on the acid-catalyzed oxygenation of 1 is important to consider here. They showed that 20 volume % TFA in CH_2Cl_2 initiates oxygenation of 1 at room temperature. Dioxetane 2 is the major product, but epoxide 19 and its acid-catalyzed rearrangement product, spiro ketone 21, are also significant products (ratios of 2:(19 + 21) of 5 to 6 were observed after 90% consumption of 1), and adamantanone was formed in low yield (1–2%). They



21



22

showed that addition of 22 powerfully inhibited the formation of oxygenated products under these conditions, but in the presence of 16 mol % 22, they observed formation of a trace (2%) of spiro ketone 21 as the sole oxidation product. They suggest that 19 and 21 are formed in a reaction manifold separate from that producing 2 and that hydroperoxy radical $HOO^\bullet$ reacts with 1 to form epoxide 19 and $HO^\bullet$, through $20^\bullet$, which is consistent with their finding 19 as the sole oxygenation product upon azoisobutyronitrile-catalyzed reaction of 1 with oxygen at 65 °C. Our results qualitatively agree with their suggestions, so it appears that formation of $20^\bullet$ by hydride donation to $B^{\bullet+}$ is the more likely of the trapping sequences. The stoichiometry of the trapping reactions using 12 also supports hydride donation. The transfer of a hydride from 12 to $B^{\bullet+}$ would produce $20^\bullet$ and anthracene after deprotonation, giving a 1:1 ratio of 19:anthracene, where as hydrogen atom donation would require a 2:1 ratio. 20^+ could well produce dioxetane 2 by cyclization and deprotonation, or it could close to epoxide 19 upon reaction with undefined nucleophiles in the reaction mixture. Another indication that $B^{\bullet+}$ might be trapped by hydride donation is that second-order rate constants for hydrogen abstraction from 11 by peroxy radicals are known not to be especially fast. Howard quotes 1480 M^{-1} s^{-1} for 11 + $HOO^\bullet$, while Porter and co-workers found rate constants under 300 M^{-1} s^{-1} for some complex alkylperoxy radicals.[15] Our work does not really establish what the trapping rate would have to be, but closure of the $B^{\bullet+}$ intermediate from 3 has been shown to be competitive with its central CC rotation rate.[6] Because $C^{\bullet+}$ opens reversibly to $B^{\bullet+}$ and the equilibrium constant is not known,[4,5] it is not obvious what the effective trapping rate constant would have to be. We unfortunately have thought of no way to more clearly define how epoxide 19 arises as the major product from trapping of $B^{\bullet+}$.

Experimental Section

General. All reactions were run under a dry nitrogen atmosphere, except where noted, in oven or flame-dried glassware. CH_2Cl_2 was dried, distilled from CaH_2, and then distilled from P_2O_5. ^1H NMR spectra (200 MHz) were recorded on an IBM WP-200 instrument and were referenced vs. Me_4Si. ^{13}C NMR spectra (50.1 MHz) were recorded on a JEOL FX-200 instrument and were referenced vs. solvent. Mass spectra were obtained on an AEI MS-902, a KRATOS MS-80 RFA, or a KRATOS MS-25 instrument. Melting points were obtained with a Thomas Hoover Unimelt apparatus and were uncorrected. TLC mesh column chromatography was performed according to Taber.[16]

Cyclic Voltammetry. Cyclic voltammetry was performed with 10-mL portions of 2 mM solutions of substrate. 7, 8, and 1 were run in 0.1 M tetrabutylammonium fluoroborate in CH_2Cl_2, but 1 was run with the addition of TFA and TFAA (20:1:1) to improve the CV waves' characteristics and reproducibility; 7 and 8 react with TFA. The CV cell was equipped with a Corning SCE reference electrode in a reference well separated from the analyte by a cracked glass bead junction, a Pt wire counter electrode, and a Pt disk working electrode polished before use with Buehler Alpha micropolish alumina 1 (5 μm) and 2 (0.3 μm). A Princeton Applied Research Model 132 electrochemical apparatus was used in conjunction with a Houston Instruments Omnigraphic Model 2000 X-Y recorder and a Tektronix Model 500 storage oscilloscope.

Preparative Ionic Hydrogenations of 7 and 8 (Table I). The preparative reactions were performed by adding the initiators in solution dropwise ($9^{\bullet+}$) or neat (HBF_4–Et_2O and TFA) by syringe to solutions of 7 or 8 in CH_2Cl_2 under the indicated conditions. Appearance of a purple coloration signaled the termination of reaction. The workup consisted of extraction with saturated Na_2CO_3, drying, filtration, and evaporation. ^1H NMR was used to examine the products, and hydrocarbons 13, mp 63–64 °C, and 15, mp 35–37 °C, were isolated by TLC mesh column chromatography with hexane as eluant. The empirical formula of 13 was determined by high-resolution mass spectroscopy to be $C_{12}H_{18}$: high-resolution mass spectrum, m/e 162.1407 obsd, 162.1408 calcd; ^1H NMR ($CDCl_3$) δ 2.27 (br s, 4 H), 2.06 (m, 6 H), 1.56 (m, 2 H), 1.42 (m, 6 H); ^{13}C NMR ($CDCl_3$) δ 48.0 (t), 47.1 (d), 41.4 (d), 25.3 (t). The structure of 15 was determined by NMR: ^1H NMR ($CDCl_3$) δ 2.20 (br s, 2 H), 2.06 (br s, 2 H), 1.70–0.80 (m, 14 H); ^{13}C NMR ($CDCl_3$) δ 50.1 (d), 42.2 (t), 41.3 (d), 36.2 (d), 34.3 (t), 31.3 (t), 24.4 (t). Assignment of structure for 13 and 15 was made on the basis of the ^{13}C NMR spectra.[17]

^1H NMR Studies on 7 and 8 (Table I). Solutions of 7 and 8 in CD_2Cl_2 under the indicated conditions in NMR tubes were treated with the appropriate initiators. The progress of the reactions were monitored by ^1H NMR after quickly warming to room temperature. The ratios of 13 and 15 to benzene were determined by integration.

Reaction of TFA with 7. 7 (100 mg, 0.624 mmol) in 0.5 mL (1.25 M) of CD_2Cl_2 in an NMR tube was treated with 48 μL (0.623 mmol) of TFA for 3 h to give a 95:5 mixture of 14 and 7. 14: ^1H NMR ($CDCl_3$) δ 2.95 (d, J = 3.3 Hz, 2 H), 2.47 (br s, 2 H), 2.30 (t, J = 4.4 Hz, 1 H), 2.20–1.80 (m, 6 H), 1.70–1.30 (m, 6 H); ^{13}C NMR ($CDCl_3$) δ 156.6 (C=O, ^2J[3F] = 44.4 Hz), 115.3 (CF_3, ^1J[3F] = 286.6 Hz), 104.8 (s), 57.5 (d), 46.0 (d), 45.6 (t), 41.0 (d), 25.0 (t), 23.9 (t). The solution was then treated with excess TFA for 2 days, treated with anhydrous K_2CO_3, filtered, and evaporated to give a 58:42 mixture of 14 and 7 by ^1H NMR.

Ionic Hydrogenation of Isopropylideneadamantane (16). 16 (100 mg, 0.567 mmol, 0.08 M) and 0.27 mL (2.8 mmol, 5.0 equiv) of 11 in 0.7 mL of CD_2Cl_2 at −78 °C in an NMR tube was treated with 10 μL (0.17 mmol, 0.30 equiv) of FSO_3H and allowed to set overnight. After warming to room temperature, the sample showed complete conversion to 2-isopropyladamantane along with 1 equiv of benzene. The sample was subjected to TLC mesh

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column chromatography with hexane as eluant, giving 100 mg of clear oil (99 % yield): ^{1}H NMR ($CDCl_3$) δ 1.90–1.60 (m, 13 H), 1.47 (d, J = 11.7 Hz, 2 H), 1.11 (d, J = 10.4 Hz, 1 H), 0.86 (d, J = 6.6 Hz, 6 H); ^{13}C NMR ($CDCl_3$) δ 51.7 (d), 39.5 (t), 38.5 (t), 31.9 (t), 29.4 (d), 28.1 (d), 27.9 (d), 27.1 (d), 20.9 (q).

Dihydroaromatic Trapping of B$^{\bullet+}$ from Biadamantylidene (1) (Table II) and from Dioxetane 2. The trapping experiments were performed by adding concentrated solutions of $9^{\bullet+}$ in CH_2Cl_2 (0.02 M) dropwise to solutions of 1 or 2 in oxygen-saturated CH_2Cl_2 at −78 °C containing 5.0 equiv of 11 or 12. The reactions were quenched with Et_3N, warmed to room temperature, and evaporated. The crude materials were tritrated thoroughly with hot pentane, filtered, and evaporated. Analysis of the product mixtures by ^{1}H NMR was facilitated by comparison to spectra of known materials, and product ratios were measured by integration.

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Halogenation of 1,5-Anhydrohex-1-enitols (Glycals). Influence of the C-6 Substituent[1]

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The stereochemistry of addition of chlorine and bromine to 3,4-di-*O*-acetyl-L-rhamnal (1), 3,4-di-*O*-acetyl-L-fucal (2), and other glycals has been investigated. Variations in the reaction conditions lead to dihalides having different configurations at C-1 and C-2. Chlorination in nonpolar solvents appears to proceed via stabilized syn ion pairs, selectively affording cis addition products. The product distribution from the bromination reactions suggests the participation of different ionic intermediates. In both chlorination and bromination, the product distribution is affected by the polarity of the solvent, the structure of the enol ether, and the nature of the halogen. The product distribution in the bromination reactions depends on the electron-withdrawing or -donating effect of the substituent at C-6. This result was interpreted in terms of the effect that the 6-substituent may exert on a nonbonding electron pair of the ring oxygen atom, affecting the stabilization of the carbocation at the anomeric center. The C-6 substituent exerts no significant effect on the chlorination reaction. Changes in the configuration of the substituents of the glycal may also modify the stereochemical course of the reaction. Thus, a change in the orientation of the acetoxy group at C-4 from equatorial (1) to axial (2) influenced the side of attack by halogen upon the double bond, leading to different ratios of cis and trans addition products from 1 and 2.

The addition of halogens to cyclic enol ethers was earlier investigated by Lemieux and Fraser-Reid,[2,3] who proposed a general mechanism involving polar attack of halogen on the double bond, resulting in formation of carbonium ions, which upon attack by halide ion lead principally to products of thermodynamic control. However, Igarashi et al.[4] established that product formation is under kinetic not thermodynamic control and that the stereoselectivity of the addition is dependent on the polarity of the solvent. Boullanger and Descotes[5] studied comparatively the addition of chlorine and bromine to acetylated and benzylated derivatives of D-glucal. The product distribution was explained on the basis of Igarashi's mechanism and a quantitative correlation established between the polarity of the solvents and the stereospecificity of the addition of chlorine. A general mechanism of chlorination of 3,4-dihydro-2*H*-pyran in several solvents, consistent with the observed solvent dependency, was proposed by Stone and Daves.[6]

In the present work, chlorination and bromination of 3,4-di-*O*-acetyl-L-rhamnal (1), 3,4-di-*O*-acetyl-L-fucal (2), and other substituted glycals has been studied as part of a synthetic program targeted toward 2′-halo derivatives of anthracycline antibiotics.[7] The 1,2-dihalides constitute useful synthetic intermediates or starting materials.[8] Product distribution obtained by halogenation of glycals under controlled conditions is discussed in terms of solvent polarity, the nature of the halogen, and the influence of steric effects in the alkene. The factors discussed here as being responsible for the product distribution during the halogenation reactions may help to explain the course of other electrophilic additions to alkenes.

Results and Discussion

Structural Assignments for the Products. Halogenation of the glycal derivatives was performed in the dark at 0 °C. The composition of the mixtures was determined by ^{1}H NMR spectroscopy and, in some instances, confirmed by analytical LC. The main products formed by the addition of chlorine or bromine (Scheme I) to the double bond of 3,4-di-*O*-acetyl-L-rhamnal (1) and 3,4-di-*O*-acetyl-L-fucal (2) were isolated by column chromatography and the minor ones purified by semipreparative LC. The structures of the resultant 2,6-dideoxy-2-haloglycosyl halides were established on the basis of their ^{1}H NMR spectra and optical rotations. It was carefully verified that

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