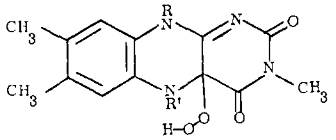
2 generates **12** as the only product in high yield.[15]

By taking advantage of the equilibrium described in eq 3, it is also possible to perform epoxidations which are catalytic in **2**. This is an attractive alternative for large-scale operations when it is desirable to avoid the handling and expense of preformed, stoichiometric quantities of **2**. The procedure involves a two-phase mixture of substrate, solvent, excess H_2O_2, and 10-15 mol % of either **2** or **3**.[16] Since the disproportionation of H_2O_2 with **3** is rather slow at room temperature,[17] these oxidations are conveniently run in 1,2-dichloroethane at reflux. The synthesis of epoxides by the catalytic method is summarized in Table II. Although 90% H_2O_2 gives the best results, 30% solutions of the oxidant can be substituted with only minor diminution in overall rate. Runs using 30% H_2O_2 could be accelerated somewhat by adding anhydrous $MgSO_4$, but the effect is not pronounced.

The electronic structure of **2** bears some similarity to the oxidized 4a-flavin hydroperoxides of type **13** which have been implicated in epoxidations and hydroxylations by external flavoprotein monooxygenases[18,19] and in the bioluminescence of bacterial luciferase.[20] The central hydroperoxide in both **2** and **13** is flanked by electron-withdrawing substituents and lies adjacent to a weakly basic, electronegative group (OH, PhNH). Like the native coenzymes, HPHl does hydroxylate arenes; mesitylene reacts with **2** to produce mesitol in 40% yield.[4a] The chemiluminescent event in bacterial luciferase has been shown by Hastings[21] to involve the combination of **13** with some endogenous aldehyde leading to a chemically excited state. Although mechanistic details are sketchy,[22] a carboxylic acid ultimately arises from the aldehyde component. Consistent with this picture, we found that *n*-heptanal formed heptanoic acid (90% yield) when treated with 1 equiv of HPHI (CH_2Cl_2, reflux, powdered Na_2CO_3). Since alcohols are inert to **2**, this selective aldehyde oxidation could prove valuable in complex synthetic manipulations.



13

We are continuing to explore these heretofore unrecognized flavin mimics and the mechanisms by which they operate.

Acknowledgment. We thank the National Institutes of Health for generous financial support.

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(15) We thank Professor Robert K. Boeckman, Jr., of Wayne State University for informing us of his results with **2** prior to publication.
(16) Hexafluoroacetone hydrate is commercially available from either Aldrich or Sigma Chemical Co.
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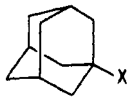
S_N2 Character of Solvolyses of *tert*-Butyl Halides and of Trifluoroacetolyses of Secondary Alkyl Sulfonates

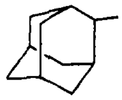
Sir:

The importance of nucleophilic solvent assistance[1] is now well established for many solvolyses, e.g., simple secondary alkyl sulfonates[2-6] and β-aryl systems.[7] We now report evidence for two additional, important, and unexpected cases of significant nucleophilic solvent assistance: (1) solvolyses of *tert*-butyl halides, key reference points for structural[8] and medium effects[9] on the reactivity of organic systems; (2) trifluoroacetolyses of simple secondary alkyl sulfonates, previously assumed to be S_N1 (limiting) reactions and used as reference points for minimum estimates of nucleophilic solvent assistance in more nucleophilic media.[2,4,10]

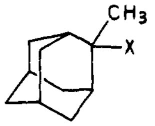
Figure 1 shows a plot of the logarithms of rate constants for solvolyses of *tert*-butyl bromide vs. 1-adamantyl bromide (I, X = Br);[11] the less nucleophilic media, acetic acid, formic acid, 97% trifluoroethanol, and 97% hexafluoropropanol (HFIP), deviate markedly from the correlation line for aqueous ethanol mixtures.



I



II



III

For these correlations, 1-adamantyl is a good reference substrate because it cannot undergo nucleophilic solvent assistance or elimination.[13] The deviations in Figure 1 are probably associated with mechanistic changes for *tert*-butyl halides which could react either by rate-limiting elimination from a contact ion pair, $k_{-1} > k_2$ in

$$RX \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} R^+X^- \xrightarrow{k_2} \text{product} \qquad (1)$$

(the currently accepted mechanism),[6,13,17] or by direct nucleophilic attack on covalent substrate, $k_2 > k_{-1}$ (not currently favored but see ref 10b, 18, and 19). These two possibilities can be distinguished by studying a substrate capable of elimination but not susceptible to nucleophilic solvent assistance. 2-Methyl-2-adamantyl chloride (III, X = Cl) is well suited for this purpose because it has been proposed to react by rate-limiting elimination from a contact ion pair,[20,21] and even solvolysis of the secondary 2-adamantyl system is thought to be free from nucleophilic solvent assistance at the α carbon atom[2,3,10b] (a fortiori for III, but solvent-assisted elimination is then possible). There is a good correlation (Figure 2) between solvolyses of *tert*-butyl chloride and III (X = Cl) for aqueous ethanols, with a major deviation for 97% HFIP almost identical

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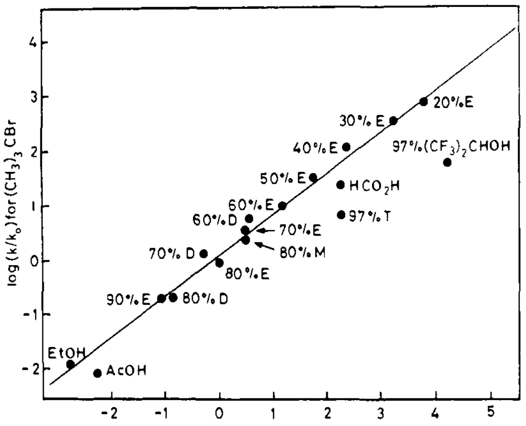

Figure 1. Rates of solvolysis of *tert*-butyl bromide vs. 1-adamantyl bromide (I, X = Br). Solvent code: % E, % v/v ethanol/water; % M, % v/v methanol/water; % D, % v/v dioxane/water; % T, % w/w CF_3CH_2OH/water. k_0 refers to 80% E. Data are from ref 6a and 13–16 assuming a Br/Cl rate ratio of 30 in 20% E and 30% E. Slope: 0.77.

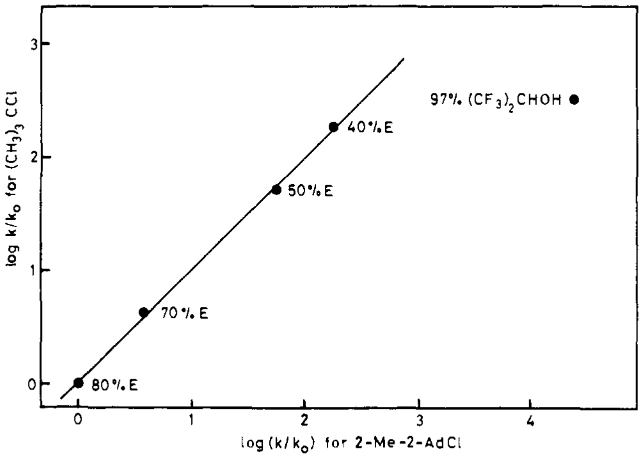

Figure 2. Rates of solvolysis of *tert*-butyl chloride vs. 2-methyl-2-adamantyl chloride (III, X = Cl). Data are from ref 20 and 22. Slope: 1.03.

with that in Figure 1. This strongly suggests that solvolyses of I and III are proceeding by the same mechanism,[23] presumably rate-determining *formation* of a contact ion pair (k_1 in eq 1) and that III is not reacting by rate-limiting elimination. Deviations in Figures 1 and 2 can be explained by nucleophilic solvent assistance in the *tert*-butyl substrates in the more nucleophilic solvents. This implies that the true carbocation reactivity of *tert*-butyl relative to 1-adamantyl systems is approached in the least nucleophilic solvent (relative rates vary from $10^{3.7}$ in ethanol to $10^{0.4}$ in 97% HFIP) and is more consistent with recently published gas-phase free energies for bromide ion transfer, showing that the 1-adamantyl cation is intrinsically more stable than the *tert*-butyl cation.[25,26]

We have also reconsidered the provisional assumption that trifluoroacetolyses of secondary alkyl sulfonates are essentially limiting processes.[2,4,29] A ρ^* correlation for solvolyses of secondary tosylates (2-propyl, 2-butyl, 2-pentyl, 3-pentyl, 4-heptyl, and pinacolyl) in HFIP (not 97%) has a slope of −9.3,[11] suggesting even higher electron demand than for trifluoroacetolyses ($\rho^* = -7.2$).[30] The calculated k_s/k_c ratio[2,4] (eq 2, where 2-AdOTs is II (X = OTs)) of only 0.29 for solvolysis of 2-propyl tosylate in HFIP suggests that it is even closer to limiting than trifluoroacetolysis. It appears that HFIP is even less nucleophilic than trifluoroacetic acid toward secondary substrates (cf. ref 31), possibly for steric reasons.

$$k_s/k_c = [k(\mathrm{ROTs})/k(\text{2-AdOTs})]_{\text{any solvent}}/[k(\mathrm{ROTs})/k(\text{2-AdOTs})]_{CF_3CO_2H} \quad (2)$$

The relative rates for solvolysis of *tert*-butyl and 2-propyl bromides are $10^{6.2}$:1 in 97% HFIP,[11] higher than observed in more nucleophilic solvents but less than the proposed limiting value of $\sim 10^8$.[24] Addition of 3% w/w water to HFIP retards solvolysis of 2-adamantyl tosylate but accelerates solvolysis of 2-propyl tosylate.[4,11] These results imply that reactions of 2-propyl tosylate in HFIP may be nucleophilically solvent assisted.

These studies are an important extension of our recent discussion of the S_N2-S_N1 spectrum and provide further evidence for nucleophilic solvation of ion-pair intermediates.[3] It seems likely that solvolyses in even less nucleophilic solvents will show structural effects on reactivity even closer to those expected from the gas-phase thermochemistry of carbocations.[25,32]

Acknowledgments. We thank the Science Research Council and the University of Manchester for financial support and Professor Paul v. R. Schleyer for helpful discussions.

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Chain Mechanism for the Autoxidation of the Isopropylchromium(III) Cation

Sir:

Primary organochromium cations in the series $(H_2O)_5CrR^{2+}$ are stable toward molecular oxygen in aqueous solution; exceptions are the benzylchromium(III) ion (which reacts indirectly by unimolecular homolysis[1]) and isopropylchromium(III) ion (and other secondary and tertiary alkyls) whose unusual reaction with O_2 is the subject of this report.

Solutions of $(H_2O)_5CrCH(CH_3)_2^{2+}$ were prepared and purified as before.[2] Kinetic studies of its reaction with oxygen were carried out using both spectrophotometric techniques and an oxygen sensing electrode. In the former case, a gentle stream of a known O_2-N_2 mixture was bubbled continuously through the spectrophotometric cell, but out of the optical path, to ensure a constant concentration of dissolved oxygen.[3]

Attempts were made to fit the data by a number of kinetic equations, but only a rate law with a 3/2-power dependence on $[CrCH(CH_3)_2^{2+}]$ gave an acceptable fit within a given run and a constant value of k_{exp} over the concentration ranges examined. A convincing illustration of the 3/2 order comes from a log-log plot of the instantaneous reaction rate vs. $[CrR^{2+}]_{av}$. A plot incorporating data from a number of runs is shown in Figure 1. The data were properly analyzed by plots constructed according to the integrated 3/2-order rate law

$$-d[CrCH(CH_3)_2^{2+}]/dt = k_{exp}[CrCH(CH_3)_2^{2+}]^{3/2}$$

The kinetic data and reaction conditions are summarized in Table I, and the average value of k_{exp} is 0.60 ± 0.10 $dm^{3/2}\ mol^{-1/2}\ s^{-1}$. The reaction rate is independent of both $[H^+]$ and $[O_2]$ over the ranges studied.

The organic products[4] consist of acetone primarily (~60% at 0.002 M H^+ to 70 ± 5% at 0.1 M H^+) and smaller amounts of 2-propanol (~30% at 0.002 M H^+ to ~20% at 0.10 M H^+); 2-propyl hydroperoxide was not detected. Although Cr(III) (a mixture of mainly $Cr(H_2O)_6^{3+}$ and smaller amounts of dimeric species) is the primary chromium product, small but reproducible yields of $HCrO_4^-$ were found (26% at 0.01 M H^+, 13% at 0.1 M H^+, 9% at 0.9 M H^+).

The following chain mechanism is consistent with the data presented:[5,6]

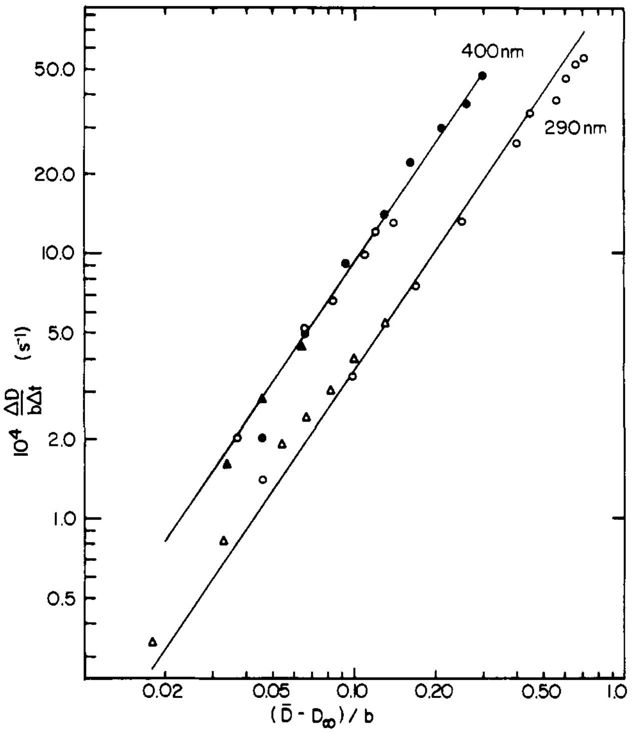

Figure 1. Determination of the 3/2 reaction order from the slopes of plots of log (instantaneous reaction rate) vs. log (mean concentration of isopropylpentaaquochromium(III) ion). Both rates and concentrations are expressed in absorbance units per 1-cm optical path, *D/b*. The plots represent data from four runs at two wavelengths with $10^3[i\text{-}C_3H_7Cr^{2+}]_0$ = 1.0 (●); 0.50 (○); 0.20 (▲); 0.10 (△). The solid lines are drawn to have slopes of exactly 3/2.

Initiation

$$CrCH(CH_3)_2^{2+} \xrightarrow{1} Cr^{2+} + \cdot CH(CH_3)_2 \qquad (1)$$

Propagation

$$O_2 + \cdot CH(CH_3)_2 \xrightarrow{2} \cdot OOCH(CH_3)_2 \qquad (2)$$

$$CrCH(CH_3)_2^{2+} + \cdot OOCH(CH_3)_2 \xrightarrow{3} CrOOCH(CH_3)_2^{2+} + \cdot CH(CH_3)_2 \qquad (3)$$

Termination

$$2 \cdot OOCH(CH_3)_2 \xrightarrow{4} (CH_3)_2C{=}O + (CH_3)_2CHOH + O_2 \qquad (4)$$

With the steady-state approximation for the chain-carrying intermediates and the assumption of a long chain length, the derived rate equation shows the proper form and identifies the experimental rate constant as the composite $k_{exp} = k_3(k_1/2k_4)^{1/2}$.

The mechanism shows the isopropylperoxochromium(III) cation as the immediate product of eq 3. This species is analogous to the well-characterized isopropylperoxocobaloxime, which has been prepared by the reaction of molecular oxygen with isopropylcobaloxime.[7] Since the $CrOOCH(CH_3)_2^{2+}$

Table I. Kinetic Data for the Reaction of O_2 and $(H_2O)_5CrCH(CH_3)_2^{2+}$ in Aqueous Perchloric Acid[a]

	initial concn ranges, M			
	$[H^+]$	$10^3[O_2]$[a]	$10^3[CrCH(CH_3)_2^{2+}]$	*k*, $dm^{3/2}\ mol^{-1/2}\ s^{-1}$ (runs)
spectrophotometry[b]	0.01-0.10	0.19-1.1	0.1-1.0	0.60 ± 0.10 (26)
O_2 electrode[c]	0.01	0.27	0.09-0.12	0.62 ± 0.11 (2)

[a] Using air, pure oxygen, and a calibrated 52:48 mixture of O_2-N_2. [b] μ = 1.00 M ($HClO_4$, $LiClO_4$); *T* = 25.0 ± 0.5 °C. [c] $\mu = [H^+]$; *T* = 22 ± 1 °C.

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