

Chlorination of Norbornane, Bicyclo[2.2.2]octane, and Adamantane Using Nitrogen Cation Radicals. Bridgehead Chlorination

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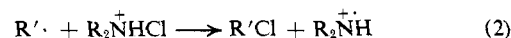
Abstract: Norbornane, bicyclo[2.2.2]octane, and adamantane have been chlorinated using nitrogen cation radicals. Norbornane gave mainly *exo*- and *endo*-2-chloronorbornane (96%); however, ~4% chlorination at the bridgehead position was observed. Bicyclo[2.2.2]octane gave 66% 1-chlorobicyclo[2.2.2]octane and 34% 2-chlorobicyclo[2.2.2]octane. This is even more pronounced with adamantane where >99% of the reaction occurs at the bridgehead position. This propensity for chlorination at the bridgehead position is attributed to steric effects. With norbornane and bicyclo[2.2.2]octane high selectivity for monochlorination was observed. In contrast, chlorination of adamantane resulted in a high yield of 1,3-dichloroadamantane.

One of the most imposing limitations placed upon synthetic organic chemistry is the lack of useful methods for selectively functionalizing an inert component of a molecule.² The site selective³ free radical chlorination of amino acids in mineral acid solvents represents such a method. More recently, Minisci⁴ and Deno⁵ have reported highly selective chlorinations at the $\omega - 1$ position of linear alcohols, ethers, amides, carboxylic acids and alkyl chlorides using dialkylammonium cation radicals ($R_2\dot{N}^+H$). In addition, unusual steric effects were noted in the chlorination of isopentane, neohexane, and 2,3-dimethylbutane when the aminium cation radical was substituted with bulky alkyl groups.⁶

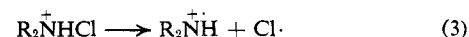
A large body of evidence supporting aminium cation radicals, $R_2\dot{N}^+H$, as the chain-carrying species in both the intramolecular (Hoffman-Löffler reaction) and intermolecular chlorination forms of R_2NCl chlorination has been presented.⁷⁻¹⁰ Neale and coworkers showed that these intermediates could be trapped by butadiene, chloroethylenes, and other alkenes.^{13,14} More recently direct observation by electron spin resonance spectroscopy

has been reported when protonated chlorodialkylamines are irradiated in an esr cavity.¹⁵

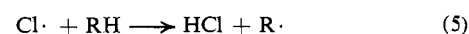
Minisci has formulated the propagation steps as eq 1 and 2.² The initiation step is much less firmly established.



The photolytic dissociation of R_2N^+HCl (eq 3)



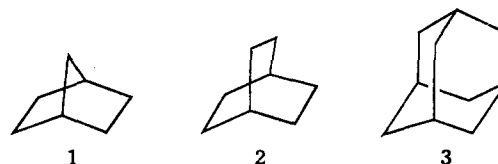
had been accepted until Neale and Walsh¹⁴ pointed out that these species do not absorb below 300 nm. They proposed that trace amounts of RN^+HCl_2 formed during the reaction and that these served as initiators. Others⁵ have proposed that small amounts of Cl_2 serve as the initiator (eq 4 and 5). We suspect that both of



these processes contribute to the initiation step.

Results

In this paper, the chlorination of norbornane (1),



bicyclo[2.2.2]octane (2), and adamantane (3) with nitrogen cation radicals is reported, including the first unassisted radical abstraction of the bridgehead hydrogen of norbornane.¹⁶

Chlorination of 1 with *N*-chlorodialkylamines in 84% H_2SO_4 at 15° led to the formation of three mono-

(15) W. C. Danen and R. C. Richard, *J. Amer. Chem. Soc.*, **94**, 3254 (1972).

(16) Freeman and coworkers have reported that chlorination of *exo*-tricyclo[3.2.1.0^{2,4}]octane with *t*-BuOCl in CCl_4 gives bridgehead chloride. The bridgehead chlorination of this compound probably results from participation by the cyclopropane ring; see P. K. Freeman, R. S. Raghaven, and G. L. Fenwick, *J. Amer. Chem. Soc.*, **94**, 5101 (1972); P. K. Freeman and R. S. Raghaven, *J. Org. Chem.*, **37**, 3670 (1972).

(1) (a) National Defense Education Act Fellow, 1970-1973; (b) Alfred P. Sloan Fellow, 1973-1975.

(2) R. Breslow, S. Baldwin, T. Flechtner, R. Kalicky, S. Kiu, and W. Washburn, *J. Amer. Chem. Soc.*, **94**, 3276 (1972), and references cited therein.

(3) J. Kollenitsch, A. Rosegay, and G. Doldouros, *J. Amer. Chem. Soc.*, **86**, 1857 (1964); see also N. C. Deno, R. F. Fishbein, and J. C. Wyckoff, *ibid.*, **92**, 5274 (1970).

(4) F. Minisci, G. P. Gardini, and G. Bertini, *Can. J. Chem.*, **48**, 544 (1970), and earlier references cited therein. Review: F. Minisci, *Synthesis*, 1 (1973).

(5) N. C. Deno, W. E. Billups, R. F. Fishbein, C. Pierson, R. Whalen, and J. C. Wyckoff, *J. Amer. Chem. Soc.*, **93**, 438 (1971). For other relevant work, see N. C. Deno, R. Fishbein, and C. Pierson, *ibid.*, **92**, 1451 (1970).

(6) N. C. Deno, R. Fishbein, and J. C. Wyckoff, *J. Amer. Chem. Soc.*, **93**, 2065 (1971).

(7) M. E. Wolff, *Chem. Rev.*, **62**, 55 (1962).

(8) W. A. Pryor, "Free Radicals," McGraw-Hill, New York, N. Y., 1966, p 280.

(9) E. J. Corey and W. R. Hertler, *J. Amer. Chem. Soc.*, **82**, 1657 (1960).

(10) The claim¹¹ that $Cl\cdot$ is the chain carrier has been convincingly refuted.^{2,12}

(11) D. D. Tanner and M. W. Mosher, *Can. J. Chem.*, **47**, 715 (1969).

(12) J. Spanswick and K. U. Ingold, *Can. J. Chem.*, **48**, 546, 554 (1970).

(13) R. S. Neale, *Tetrahedron Lett.*, 483 (1966); *J. Amer. Chem. Soc.*, **86**, 5340 (1964); R. S. Neale and L. A. Hinnan, *ibid.*, **85**, 2666 (1963).

(14) R. S. Neale and M. R. Walsh, *J. Amer. Chem. Soc.*, **87**, 1255 (1965).

chlorides shown by isolation and comparison with authentic samples to be 1-chloronorbornane (**4**), *exo*-2-chloronorbornane (**5**), and *endo*-2-chloronorbornane. The results are summarized in Table I. Chlorination

Table I. Chlorination of Norbornane by *N*-Chlorodialkylamines in 84% H₂SO₄ at 15°

Method	Conversion	% mono-chlorides	% poly-chlorides	% 4	% 5	% 6
Me ₂ NCl/84% H ₂ SO ₄	16	16			11	5
	47	42	5	<1	28	13
Et ₂ NCl/84% H ₂ SO ₄	55	55		1	34	20
<i>i</i> -Pr ₂ NCl/84% H ₂ SO ₄	34	34		<1	20	14
	58	58		2	34	22
	85	83	2	4	48	32
	99	89	10	3	52	34
	100	81	18	3	47	31
Cl ₂ /CCl ₄	6	4	2		3	2
	24	15	10		10	5
	44	25	18		17	8
	54	29	26	~0.1	20	9
Cl ₂ /CH ₂ Cl ₂ /reflux	10	8	2		5	2
	22	17	6		11	5
	30	21	10	~0.1	14	7
Cl ₂ /84% H ₂ SO ₄	7	6	2		4	2
	12	9	3		6	3
	22	16	6		11	5
	24	17	7		12	5
<i>tert</i> -Butyl hypochlorite	35	28	7	~0.4	25	3

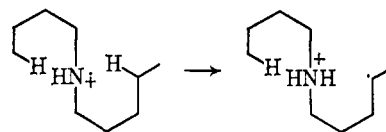
of **2** with *i*-Pr₂NCl in 84% H₂SO₄ gave 1-chlorobicyclo[2.2.2]octane (**7**) and 2-chlorobicyclo[2.2.2]octane (**8**) in a ratio of about 2:1. In sharp contrast, chlorination of **2** with Cl₂ in CCl₄ at 15° gave **7** and **8** in a ratio of 1:4.7. Chlorination of **3** gave two major products identified as 1-chloroadamantane (**9**) and 1,3-dichloroadamantane (**10**). Curiously, other chlorides were not produced in significant yields at low conversions. Thus, chlorination of **3** to 98% conversion gave 60% **9**, 37% **10**, and ~0.7% 2-chloroadamantane (**11**). At still higher conversion the composition was shown by glpc to be 64.5% **10** and 35.5% **9**. At this point glpc analysis revealed the appearance of other polychlorides. Chlorination of **3** with Cl₂ in CCl₄ at 15° gave 47% **9** and 53% **11**.

Discussion

Bridgehead Chlorination. The most striking feature of these data is the unusually large amount of bridgehead chlorination, although repetition of earlier works¹⁷ on chlorination of norbornane with Cl₂ in CCl₄ (Table I) revealed that a small but reproducible amount (~0.1%) of **4** is produced. With *t*-BuOCl a slightly higher yield of **4** (Table I) was observed. This is even more pronounced with **2** (66% chlorination at C₁) and **3** (99% chlorination at C₁) where bridgehead chlorination accounts for the major reaction pathway. We attribute these results solely to steric effects. Inspection of molecular models clearly reveals that the bridgehead hydrogens of these hydrocarbons are much less encumbered for hydrogen abstraction than their C₂ counterparts. This steric effect is particularly empha-

(17) E. C. Kooyman and G. C. Vegter, *Tetrahedron*, **4**, 383 (1958); J. D. Roberts, J. Urbanek, and R. Armstrong, *J. Amer. Chem. Soc.*, **71**, 3049 (1949).

sized with norbornane, where bridgehead chlorination is observed even though it is well established that aminium cation radicals are very sensitive to carbon-hydrogen bond strength. This is illustrated in the Hofmann-Löffler reaction of *N*-chloro-*N*-*n*-butyl-*N*-*n*-amylamine where hydrogen abstraction occurs exclusively at the secondary position.⁹



Selectivity for Monochlorination. In addition to the high ω - 1 selectivity observed by Minisci⁴ and Deno,⁵ chlorinations by *N*-chlorodialkylamines are highly selective for monochlorination. This high selectivity is a result of the fact that hydrogen atom abstraction by the dialkylaminium cation radical, R₂N⁺H, takes place remote from both protonated functions (ether, acid, amine, and alcohol) and the chloro substituent. This is emphasized in the chlorination of norbornane (Table I) where <20% polychlorination was found at 99% norbornane conversion. However, this propensity for monochlorination was not observed in the chlorination of adamantane, where large amounts of 1,3-dichloroadamantane were observed at relatively low conversion. If selectivity for monochlorination results from long-range inductive deactivation for chloroalkanes as suggested by Minisci,⁴ then the observed rapid formation of 1,3-dichloroadamantane cannot be readily understood. It may be a consequence of the sterically unique adamantane molecule or special electronic factors associated with this system.

Exo/Endo Ratios for Norbornane Chlorinations. No distinction was made (Table I) in the abstraction of the *exo*- and *endo*-2-norbornyl hydrogen. This ratio, although not presently known, would be valuable in understanding the reactivity of the 2-norbornyl position. The atom transfer to the 2-norbornyl radical more readily offers itself to study. This is the step that determines the *exo/endo* of 2-chloronorbornane and is a function of the atom donor rather than the origin of the 2-norbornyl radical.¹⁸ The *exo/endo* ratios for several chlorinations are shown in Table II. These ratios

Table II. Exo/Endo Ratios in Chlorine Atom Donation to the 2-Norbornyl Radical

Atom donor	Exo/endo ratio
Me ₂ N ⁺ HCl	68/32
Et ₂ N ⁺ HCl	63/37
<i>i</i> -Pr ₂ N ⁺ HCl	60/40
Cl ₂ /CCl ₄	68/32
Cl ₂ /CCl ₄	72/28 ^{a,b}
Hexachlorocyclopentadiene	55/45 ^a
Tetrachlorocyclopropene	78/22 ^a
<i>tert</i> -Butyl hypochlorite	89/11

^a Value obtained from ref 18. ^b Run at 80°

cannot be readily explained in terms of steric effects for chlorination by *N*-chlorodialkylamines since one would expect a mild steric trend toward formation of *exo*-2-chloronorbornane (**5**). Blank experiments failed to

(18) P. D. Bartlett, G. N. Fickes, F. C. Haupt, and R. Helgeson, *Accounts Chem. Res.*, **3**, 177 (1970), and references cited therein.

uncover any tendency toward formation of the reported 80/20 equilibrium mixture, and also ruled out rearrangement as a source of bridgehead chlorides (see Experimental Section). Since the R_2NCl chlorinations were run with CCl_4 cosolvent, it was necessary to investigate the effect of CCl_4 on the measured exo/endo ratios. Indeed, when CCl_4 was used in excess, the measured exo/endo ratios were altered toward the 98/2 value reported by Bartlett. However, the norbornane solutions used for the chlorination with R_2NCl were held at 0.675 M, thus keeping the participation by CCl_4 reasonably constant.

Atom transfer to the 2-apocamphyl radical is reported to favor exo chlorination when the chlorine is more nucleophilic. Thus, transfer to the 2-apocamphyl radical from hexachlorocyclopentadiene gave a 55/45 ratio of exo and endo chlorides, whereas tetrachlorocyclopropene gave a 78/22 mixture. This concept gains additional support from the work of Davies and Parrott,¹⁹ which shows an increase in exo attack with increasing nucleophilicity in the radical addition of alkylthiols to 1,4,7,7-tetramethylnorbornene. The latter case involves reaction with a norbornene, but if the 2-norbornyl radical exhibits sp^2 hybridization as depicted by Bartlett,¹⁸ then the norbornyl reaction center should be very similar.

We find that the reaction of *tert*-butyl hypochlorite with the norbornyl radical produces an 89/11 exo/endo ratio. The $Cl\cdot$ from this donor is more nucleophilic than the chlorine from R_2N^+HCl which gives ratios from 68/32 to 60/40. Within this set the effects are small, but if this small trend is a result of the electronic character of the chlorine atom transfer step, then the chlorine atom from $(CH_3)_2\dot{N}^+H$ is more nucleophilic than those of larger alkyl substitution. Since the gas phase basicities of amines are known²⁰ to exhibit an opposite relationship to alkyl size, an electronic explanation of the observed trend would imply steric hindrance to solvation of the cation, thus increasing its effective positive charge relative to $(CH_3)_2\dot{N}^+H$.

The effect of nucleophilicity on the exo/endo ratios may lie in its effect on the position of the transition state on the reaction coordinate. This would manifest itself in the torsional strain²¹ felt in endo attack and would be at a maximum if the transition state coincided with the eclipsing of the C_1 and C_2 C-H bonds. However, there is not enough evidence at hand to clearly support or dismiss this explanation.

Relative Reactivities. Relative reaction rates of **1**, **2**, and **3** with *N*-chlorodiisopropylamine in 84% H_2SO_4 at 15° were measured. Since a large body of information is available for comparison of both free radical and ionic reactions, it was thought that a relative rate study would yield useful information regarding the observed bridgehead abstractions. These results are listed in Table III along with the results of several related investigations. The best comparison is found in the study of Koch and Gleicher²² on the photochemical bromination of **1**, **2**, and **3** with bromotrichloromethane.

(19) D. I. Davies and M. J. Parrott, *Tetrahedron Lett.*, **27**, 2719 (1972).

(20) J. T. Brauman, J. M. Riveros, and L. K. Blair, *J. Amer. Chem. Soc.*, **93**, 3914 (1971).

(21) P. v. R. Schleyer, *J. Amer. Chem. Soc.*, **89**, 701 (1967).

(22) V. R. Koch and G. J. Gleicher, *J. Amer. Chem. Soc.*, **93**, 1657 (1971).

Table III. C_1 vs. C_2 Reactivities in Norbornane, Bicyclo[2.2.2]octane, and Adamantane

Reaction	Substrate	Product composition		Relative reactivity	
		% C_1	% C_2	C_1	C_2
$R_2\dot{N}^+H$ abstraction	Adamantane	99	1	1.0	0.003
	Bicyclo[2.2.2]octane	66	34	1.21	0.10
$CCl_3\cdot$ abstraction	Norbornane	4	96	0.06	0.33
	Adamantane	86	14	1.0	0.05
$Cl\cdot$ chlorination	Bicyclo[2.2.2]octane	9	91	1.12	1.92
	Norbornane	0	100	0	0.67
	Adamantane	47	53		
Decarbonylation of C_1 aldehydes ^c	Bicyclo[2.2.2]octane	18	82		
	Norbornane	0.1	99.9		
	Adamantane			1.0	
Bromide ^d solvolysis	Bicyclo[2.2.2]octane			0.5	
	Norbornane			0.0003	
	Adamantane			1	
	Bicyclo[2.2.2]octane			10^{-3}	
	Norbornane			10^{-10}	

^a Per hydrogen atom. ^b Reference 18. ^c Reference 23. ^d R. C. Font, Jr., and P. v. R. Schleyer, *Advan. Alicyclic Chem.*, **1**, 283 (1966).

Their study is similar to the one reported here in that the radicals are generated by hydrogen atom abstraction.

The main difference between the data presented by Koch and Gleicher and the results reported here is the more than tenfold difference in relative reactivities of the C_2 hydrogens in adamantane and bicyclo[2.2.2]octane toward the two reagents. Again this probably reflects steric crowding in the transition state for abstraction at C_2 . The trichloromethyl radical is not free of steric demands, but comparison of the reactivities with the calculated energy values reported by Gleicher²² (Table IV) indicates that increased sensitivity to the

Table IV. Calculated Changes in Strain Energy^{a,b}

Substrate	C_1	C_2
Norbornane	+6.032	-2.417
Bicyclo[2.2.2]octane	+0.487	-4.042
Adamantane	0	-1.139

^a Values obtained from ref 22. ^b Defined as $\Delta\Delta H = \Delta H_{\text{substrate}} - \Delta H_{\text{adamantane}}$ where $\Delta H = H_{\text{tss}} - H_{\text{gss}}$, where tss is transition state strain and gss is ground state strain.

stability of the available transition states will not explain the difference.

However, a comparison of the steric demands of the abstraction step provides a more plausible correlation, with $R_2\dot{N}^+H$ being more sensitive to steric crowding than the trichloromethyl radical. This idea is consistent with the explanation proposed by Tabushi²³ in his studies of radical reactions of adamantane.

The adamantyl C_2 hydrogens are sterically true chair cyclohexane axial hydrogens. The relevant structure for **2** is the boat form of cyclohexane of **1**. Since the C_2 position in **2** is more strongly deactivated in the $R_2\dot{N}^+H$ reaction than in **3**, the explanation of steric control is reasonable. Further, the $R_2\dot{N}^+H$ relative reactivity of the 2-norbornyl position can be understood in terms of a strongly hindered endo reaction and a less demanding exo reaction.

(23) I. Tabushi, Y. Aoyama, S. Kojo, J. Hamuro, and Z.-I. Yoshida, *J. Amer. Chem. Soc.*, **94**, 1177 (1972).

Applequist's²⁴ work represents perhaps a more direct measure of radical stability, but the possible existence of influences of the decarbonylation step might prevent this partitioning from accurately reflecting the relative stabilities of the radicals. Tabushi's²³ work demonstrates that the relationship between reactivity and selectivity is not always straightforward. At the same time Applequist's work does not reflect the selectivities of hydrogen atom abstraction and is therefore useful since it is complementary to this study. The bromide solvolysis rates clearly demonstrate that the observed bridgehead reactivities cannot be explained in terms of polar contributions to the transition state of the abstraction step.

Experimental Section

General. Nmr spectra were recorded on Varian A-56/60A and Perkin-Elmer R12A spectrometers in CCl₄ solution and results are expressed in parts per million downfield from internal TMS. Infrared spectra were recorded (neat) on a Beckman IR-8 spectrometer. Glpc analyses were carried out on Model 700 and Model 5705A Hewlett-Packard instruments with thermal conductivity detectors. Specific columns and conditions are noted with the individual experiments. Experimentally determined area calibration factors were used when comparing dissimilar compounds (unless noted), but isomeric chloroalkanes were assumed to have equal molar response factors. Peak areas were determined by the product of height and width at half-height. In most cases the data tabulated are the averages of from three to ten experiments.

Materials. Sulfuric acid was degassed by continuous N₂ purging several days before use. All reactions were run in an N₂ atmosphere. All solvents were reagent grade and were used without further purification.

N-Chlorodimethylamine was prepared from *N*-chlorosuccinimide (NCS) and anhydrous dimethylamine in CCl₄ at 8°. The reaction mixture was then warmed with stirring to room temperature overnight and the *N*-chlorodimethylamine, bp 44–46°, distilled into an ice-cooled receiver from the reaction vessel through a 1-ft column packed with glass helices. All other *N*-chlorodialkylamines were prepared from the corresponding dialkylamines and NCS in ether at 25°. *N*-Chlorination was complete in 1 hr and the succinimide was removed by filtration. The ether solution was then washed with 2.5 *N* H₂SO₄ and H₂O and dried over CaSO₄, and the solvent was removed *in vacuo* to leave crude R₂NCl, which was used without further purification.

Norbornane (**1**) was prepared by hydrogenation of norbornene (Aldrich) over palladium on powdered charcoal in pentane. Impurities were removed by washing the pentane solution with 96% H₂SO₄ until the acid phase remained colorless. The organic layer was washed with H₂O, bicarbonate, water, and finally saturated NaCl solution. The pentane solution was then dried over CaSO₄, and after removal of solvent the norbornane was distilled at 105°. Similarly, **2** was prepared from bicyclo[2.2.2]oct-2-ene²⁵ and sublimed at 100° (20 mm). Adamantane (Aldrich Chemical Co.) was sublimed before use. 1-Chloronorbornane (**4**) was prepared by the method of Wiberg.²⁶ 7-Chloronorbornane was prepared as described by Roberts,²⁷ although we found it advantageous to purify the intermediate 7-chloronorborn-5-ene by preparative glpc (6 ft × 0.25 in. 20% Ucon 50HB280X polar column operated at 130°) before hydrogenation. *exo*-2-Chloronorbornane (**5**) was prepared by the method of Schmerling.²⁸ A 60:40 mixture of *endo*-2-chloronorborn-5-ene and *exo*-2-chloronorborn-5-ene was prepared by reaction of cyclopentadiene and vinyl chloride at 190° for 24 hr. Crude distillation followed by preparative glpc (6 ft × 0.25 in. UCON 50HB280X polar on 80–100 mesh Chromosorb P operated at 150°) gave pure *endo*-2-chloronorborn-5-ene which

was hydrogenated over PtO₂ in ether to give **6**. *endo*-2-Chloronorborn-5-ene had a longer glpc retention time than the *exo* isomer.

Chlorination of Norbornane (1). In a typical experiment a solution of **1** (2 g, 20.8 mmol) in 10 ml of CCl₄ was added to 50 ml of 84% H₂SO₄ in a 100 ml three-neck flask fitted with a mechanical stirrer, condenser, N₂ inlet, and addition funnel. The solution was cooled to 15° and *N*-chlorodiisopropylamine (3 g, 22.1 mmol) added dropwise. The solution was then irradiated at 15° with a sun lamp. The reaction was followed by removal of 2-ml aliquots, which were added to ice-water and extracted with 1 ml of CCl₄ and dried over CaSO₄. Glpc (6 ft × 1/8 in. SE-30 column held at 60° for 4 min, then programmed at 4° min⁻¹ to 160°) showed two monochloride bands, A and B (order of increasing retention time). The minor component A was isolated by preparative glpc and shown to be **4** by comparison of its nmr spectrum with an authentic sample. Component B proved to be a mixture of **5** and **6**.²⁹ Efforts to separate these isomers by glpc failed.³⁰ Determination of *exo/endo* ratios was accomplished by nmr analysis. Integration of the nmr signal for the α hydrogens of mixtures of the isomers readily provided this ratio. The α hydrogen of **6** has a signal (complex multiplet) centered at δ ~4.17, whereas the *exo* isomer **5** exhibits its signal at δ 3.80.

In a second run, **1** (2 g, 20.8 mmol) dissolved in 10 ml of CCl₄ was added to a mixture of *N*-chlorodiisopropylamine (3 g, 22.1 mmol) in 50 ml of 84% H₂SO₄ at 15°. Irradiation was begun and the reaction monitored by removal of three 2-ml aliquots at periodic intervals. At 75% conversion (based on **1**) the mixture was poured onto ice and the organic fraction extracted with CCl₄. Work-up followed by distillation gave 1.71 g of product shown by glpc to be 94% 2-chloronorbornane (**5** and **6**), 4% **4**, and 2% **1**. This corresponds to 13.1 mmol of monochloride (63% theoretical). Correction for the aliquot removal and conversion (75%) indicates an isolated yield of 93.5%. Evidence against isomerization or destruction of the 2-chloronorbornanes **5** and **6** being responsible for the observed product ratio was provided by quantitative recovery of these (CCl₄ solution) after 48 hr contact (25°) with 84% H₂SO₄. In another experiment, pure **5** in CCl₄ was stirred in 84% H₂SO₄ for 24 hr. Nmr and glpc analysis failed to detect any change in composition. The stirred mixture was then irradiated for 24 hr without change. Diisopropylamine (1 g) was added and irradiation continued for 24 hr. Again no change was detected and the infrared spectrum of the isolated material was identical with starting **5**.

Chlorination of Bicyclo[2.2.2]octane (2). Hydrocarbon **2** (1 g, 9.1 mmol) dissolved in 10 ml of CCl₄ was added to a solution of *N*-chlorodiisopropylamine (2 g, 14.8 mmol) in 50 ml of 84% H₂SO₄ and the solution irradiated (sunlamp) with stirring at 15°. Glpc analyses (6 ft × 1/8 in. 20% SE-30 on 80–100 mesh Chromosorb W column operated at 125°) showed two major products with retention times corresponding to authentic **7** and **8** (order of increasing retention time) prepared from **2** and Cl₂. Additional evidence for structural assignment was provided by nmr spectra of materials after purification by preparative glpc. Chloride **7** showed a broad multiplet centered at δ 1.18. The remaining isomer showed a one-proton signal at δ 4.13 (CHCl) expected for **8**.

Chlorination of Adamantane (3). Hydrocarbon **3** (2 g, 14.7 mmol) was dissolved in 15 ml of CCl₄ and added to a solution of *N*-chlorodiisopropylamine (2 g, 14.8 mmol) in 50 ml of 84% H₂SO₄ and irradiated at 15°. Glpc analysis (6 ft × 1/8 in. SE-30 column operated at 155°) revealed three components corresponding to **9**, **10**, and **11**. **11** shows nmr signals at δ 1.63 (s, 2 H), 2.07 (s, 8 H), 2.30 (s, 2 H), and 2.44 (s, 2 H).

In a second run, **3** (0.83 g, 6.09 mmol) was dissolved in 8.5 ml of CCl₄ and added to 50 ml of 84% H₂SO₄ containing 4 g (30 mmol) of *N*-chlorodiisopropylamine. The solution was stirred and irradiated with two sun lamps for 48 hr. The reaction mixture was then added to ice-water, extracted with CCl₄, washed, and dried, and the solvent was removed. Sublimation at 105° (3 mm) gave 0.995 g of white solid identified by glpc (uncorrected for differences in molar responses) as **9** (35.5%) and **10** (64.5%). This corresponds to an isolated yield of 90%.

(24) D. E. Applequist and L. Kaplan, *J. Amer. Chem. Soc.*, **87**, 2194 (1965).

(25) We thank Dr. Kenneth Greenlee for providing a sample of bicyclo[2.2.2]oct-2-ene.

(26) K. B. Wiberg, B. R. Lowry, and T. H. Colby, *J. Amer. Chem. Soc.*, **83**, 3998 (1961).

(27) J. D. Roberts, F. O. Johnson, and R. A. Carboni, *J. Amer. Chem. Soc.*, **76**, 5692 (1954).

(28) L. Schmerling, *J. Amer. Chem. Soc.*, **68**, 195 (1946).

(29) Kooyman and Vegter¹⁷ reported the formation of small amounts of 7-chloronorbornane in the chlorination of norbornane with Cl₂. This material was not detectable in our product mixtures by either ir or nmr spectroscopy; however, it was not possible to use more sensitive glpc techniques due to a coincidence of retention times.

(30) M. L. Poutsma, *J. Amer. Chem. Soc.*, **87**, 4293 (1965), noted this problem. Reference 18 reports separation of these isomers on a capillary column.

Relative Rates. Mixtures of **1** (2 mmol) and either 2 mmol of **2** or **3** were diluted with CCl_4 to 4 ml. This solution was analyzed and added to 50 ml of degassed H_2SO_4 . The mixture was stirred mechanically and sampled by removal of 1-ml aliquots which were added to ice-water and extracted with an additional 1 ml of CCl_4 . The CCl_4 solution was dried and analyzed by glpc (6 ft \times $\frac{1}{8}$ in. 10% Apiezon J on Chromosorb W column). Mixtures of **1** and **3** were analyzed at 90° for 8 min followed by temperature programming (32 deg min^{-1}) to 160° . Mixtures of **1** and **2** were analyzed at 90° for 8 min then programmed (8 deg min^{-1}) to 160° . *N*-Chlorodiisopropylamine was then added and the solution irradiated under N_2 at 15° with two sun lamps. Aliquots were periodically removed and analyzed. Norbornane conversion was computed on the percentage of norbornyl materials present as starting material and the disappearance of the other hydrocarbon

measured from this by using the predetermined conversion factor. These data were then converted to relative reactivities as described by Poutsma.³¹

Acknowledgment. We gratefully acknowledge the Robert A. Welch Foundation and Eli Lilly for support of this work. Acknowledgment is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for partial support. The authors are also grateful to Dr. E. S. Lewis for many helpful discussions.

(31) M. L. Poutsma, *J. Amer. Chem. Soc.*, **87**, 4285 (1965).

Ambident Behavior of Some Phenols and Alkoxy Benzenes in Antimony Pentafluoride-Fluorosulfonic Acid Mixtures¹

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Abstract: The position of protonation of several alkyl-substituted phenols and alkoxy benzenes has been studied in several $\text{SbF}_5\text{-FSO}_3\text{H}$ mixtures as a function of temperature. Carbon and oxygen protonation follow different acidity functions and oxygen protonation is slightly more exothermic than carbon protonation, the differences increasing as the antimony pentafluoride concentration increases. The ratio of O:C protonation is sensitive to the nature and concentration of solutes such as SO_2 , H_2O , and the organic base. Because of this, it appears that measurements at nmr concentrations will be unsuitable for quantitative studies of such systems. Structural effects on the ambident behavior vary with acid concentration and are not well understood.

Hydroxy and alkoxy aromatics are one of the most thoroughly studied classes of ambident bases. These molecules can be protonated on either carbon or oxygen; the position of protonation varies in complex patterns, and the factors controlling this variation are not yet understood. If the factors influencing the ambident behavior of these molecules could be isolated and understood, these molecules might constitute a very useful probe of solvent-solute interactions in strong acid systems. To this end we have examined the behavior of a few such ambident bases in mixtures of antimony pentafluoride and fluorosulfonic acid.

There is a good review of this area,² but because of much recent activity it is somewhat out of date. There is also a brief discussion of the behavior of alkyl aryl ethers in Olah's review.³ For trihydroxy compounds, carbon protonation predominates in sulfuric and perchloric acid.⁴ In superacids, initial protonation of the trihydroxy and trialkoxy compounds always occurs at carbon, but a second proton can be added at either carbon or oxygen to give a dication.⁵ Even with dicat-

ion formation, carbon protonation predominates. Except for hydroquinone and *p*-dimethoxybenzene which protonate on oxygen, the dihydroxy and dialkoxy benzenes show predominantly carbon protonation.⁶ Some oxygen protonation occurs with *o*-dimethoxybenzene.

The bases showing the most complex behavior, perhaps because they have received the most attention, are anisole and *p*-methylanisole. Early work with these was complicated by the fact that they sulfonate very readily.^{7,8} Both of these compounds are ambident bases as shown in Scheme I and their protonation behavior in various solvents is complex.^{6,9-12} In addition to these two compounds other methyl-substituted phenols and anisoles,^{6,13-15} and halogen-substituted

(1) Some of this work has appeared in preliminary form: J. W. Larsen and M. Eckert-Maksić, *Tetrahedron Lett.*, 1477 (1972).

(2) D. M. Brouwer, E. L. Mackor, and C. MacLean in "Carbonium Ions," Vol. II, G. A. Olah and P. v. R. Schleyer, Ed., Wiley, New York, N. Y., 1970.

(3) G. A. Olah, A. M. White, and D. H. O'Brien, *Chem. Rev.*, **70**, 561 (1970).

(4) A. J. Kresge, Y. Chiang, and L. E. Hukka, *J. Amer. Chem. Soc.*, **93**, 6161 (1971), and references therein.

(5) G. A. Olah and Y. K. Mo, *J. Amer. Chem. Soc.*, **94**, 5341 (1972).

(6) G. A. Olah and Y. K. Mo, *J. Org. Chem.*, **38**, 353 (1973).

(7) B. G. Ramsey, *J. Amer. Chem. Soc.*, **88**, 5358 (1966).

(8) U. Svonholm and V. D. Parker, *J. Chem. Soc. Perkin Trans. 2*, 962 (1972).

(9) T. Birchall, A. N. Bourns, R. J. Gillespie, and P. J. Smith, *Can. J. Chem.*, **42**, 1433 (1964).

(10) T. Birchall and R. J. Gillespie, *Can. J. Chem.*, **42**, 502 (1964).

(11) D. M. Brouwer, E. L. Mackor, and C. Maclean, *Recl. Trav. Chim. Pays-Bas*, **85**, 109 (1966).

(12) G. A. Olah, M. B. Comisarow, E. Nemanworth, and B. Ramsey, *J. Amer. Chem. Soc.*, **89**, 5259 (1967).

(13) J. W. Larsen and M. Eckert-Maksić, *Croat. Chem. Acta*, **45**, 503 (1973).

(14) M. P. Hartshorn, K. E. Richard, J. Vaughn, and G. J. Wright, *J. Chem. Soc. B*, 1624 (1972).

(15) G. Bertholon and R. Perrin, *C. R. Acad. Sci., Ser. C*, **275**, 645 (1972).