Stable Carbocations. CLXXI.[1,2] 1-Fluoro(Chloro)-1-cycloalkyl Cations. Further Data on the Effect of Halogen Back-Donation and the Stability of Halocarbenium Ions

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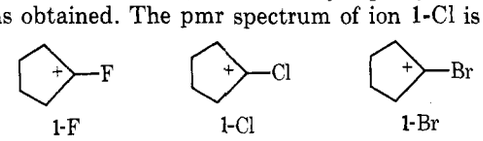
A series of 1-fluoro(chloro)-1-cycloalkyl cations have been prepared and investigated under stable ion conditions. The structure of the ions was studied by proton, carbon-13, and fluorine-19 nmr spectroscopy. Chlorocarbenium ions were found to be less stable than their corresponding fluorocarbenium ions, wherein strong fluorine "back-donation" is the dominant factor to stabilize these ions.

Extensive work has been carried out on the study of stable carbocations in this laboratory.[3] The influence of substitution by heteroatoms, especially halogen atoms, on the stability of carbenium ions has been noticed.[4] We have studied the carbon-13 nmr of dimethylhalocarbenium ions and found that the degree of halogen "back-donation" in these ions is dependent on the electronegativity of the halogen atoms.[4d]

Among the reported various types of halogen-substituted carbenium ions,[4,5] cyclic halocarbenium ions are of particular interest. Recently we have reported the preparation of 2-halonorbornyl cations and found that only the 2-fluoronorbornyl cation was stable under low-nucleophilicity superacid media.[4e] The 2-chloro- and 2-bromonorbornyl cations were rearranged to the corresponding protonated 4-halonortricyclenes under similar conditions. We how have undertaken a detailed study of monocyclic chloro- and fluorocarbenium ions by ^1H, ^{13}C, and ^{19}F nmr spectroscopy. The degree of halogen "back-donation" in halocarbenium ions is discussed based on the observed nmr data and the relative stabilities of these ions.

Results and Discussion[6]

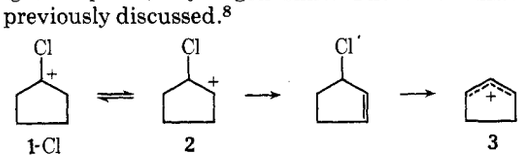
1-Halo-1-cyclopentyl Cations. When 1,1- or *trans*-1,2-dichlorocyclopentane was treated with SbF_5–SO_2ClF (SO_2) solution at −78°, 1-chloro-1-cyclopentyl cation (**1**-Cl) was obtained. The pmr spectrum of ion **1**-Cl is shown



1-F **1**-Cl **1**-Br

in Figure 1. As expected, it displays a AA′BB′ type coupling, somewhat similar to that of tetramethylenehalonium ions,[7a] but with substantial deshielding, particularly of the α-methylene protons, a good indication for ion **1**-Cl. The proton chemical shifts of ion **1**-Cl are solvent dependent (Table I). In the less nucleophilic SO_2ClF medium, more deshielded absorptions are observed. Similar observation was found in many other carbocations.[7b]

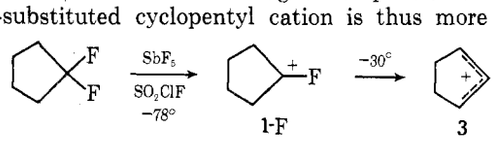
The formation of ion **1**-Cl from *trans*-1,2-dichlorocyclopentane is interesting and may involve the initial formation of the 2-chloro-1-cyclopentyl cation **2**, which then undergoes rapid 1,2-hydrogen shift. The mechanism has been previously discussed.[8]



1-Cl **2** **3**

In contrast, when 1,1-dibromocyclopentane was treated with SbF_5–SO_2ClF solution at −120°, the corresponding 1-bromo-1-cyclopentyl cation **1**-Br was not observed,[8] only formation of the cyclopentenyl cation **3**. The pmr spectrum of ion **3** has been reported previously.[8] The 1-chloro-1-cyclopentyl cation **1**-Cl is also not stable above −60° and slowly transforms into ion **3**. The mechanism for such transformation may involve a reversible 1,2-hydrogen shift between **1** and **2** with subsequent deprotonation and ionization leading to the formation of ion **3**.[8] It is thus suggested that this process may be extremely rapid (even at −120°) in the case of transformation of 1-bromo-1-cyclopentyl cation **1**-Br (not observable) to ion **3**.

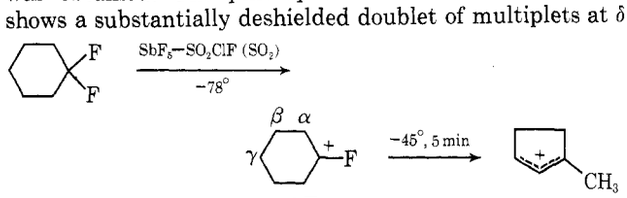
The 1-fluoro-1-cyclopentyl cation **1**-F could be prepared at −78° when 1,1-difluorocyclopentane was treated with a SbF_5–SO_2ClF solution. It was stable at temperatures below −30°, but formed **3** at higher temperature. The fluorine-substituted cyclopentyl cation is thus more stable



1-F **3**

than its chlorine-substituted analog, which in turn is more stable than the bromine analog. In SbF_5–SO_2 solution, ion **1**-F was unstable even at −60° and quickly gave ion **3** upon short standing. The pmr spectrum of **1**-F (Figure 1) consists of a set of doublet multiplets centered at δ 4.25 (J_{HF} = 12 Hz) and a pentet at δ 3.04, in a ratio of 1:1. The ^{19}F nmr spectrum of **1**-F displays a deshielded quintet at φ −149.4 from external CCl_3F.

1-Halo-1-cyclohexyl Cations. When 1,1-difluorocyclohexane was treated with SbF_5–SO_2ClF (SO_2) solution at −78°, the corresponding 1-fluoro-1-cyclohexyl cation **4**-F was obtained. The pmr spectrum of ion **4**-F (in SO_2) shows a substantially deshielded doublet of multiplets at δ



4-F **5**

3.95 (J_{HF} = 20 Hz) for the α-methylene protons (Figure 1). The β- and γ-methylene proton absorptions are two multiplets at δ 2.38 and 2.10 (in a ratio of 2:1). The ^{19}F nmr spectrum of ion **4**-F displays a highly deshielded quintet at φ −166.5 (from $CFCl_3$). All these data clearly suggest the formation of ion **4**-F. The proton chemical shifts of ion **4**-F are more deshielded in less nucleophilic SO_2ClF than in SO_2 (Table I). Ion **4**-F is slowly transformed to the methylcyclopentenyl cation **5** at higher temperature (*e.g.*, 5 min at −45°). Ion **5** could be readily identified by comparing the pmr spectrum with that of the ion reported previously.[8]

The 1-chloro-1-cyclohexyl cation **4**-Cl could only be formed from 1,1-dichlorocyclohexane in SbF_5–SO_2ClF solution at −120°. (When the dichloride was ionized at

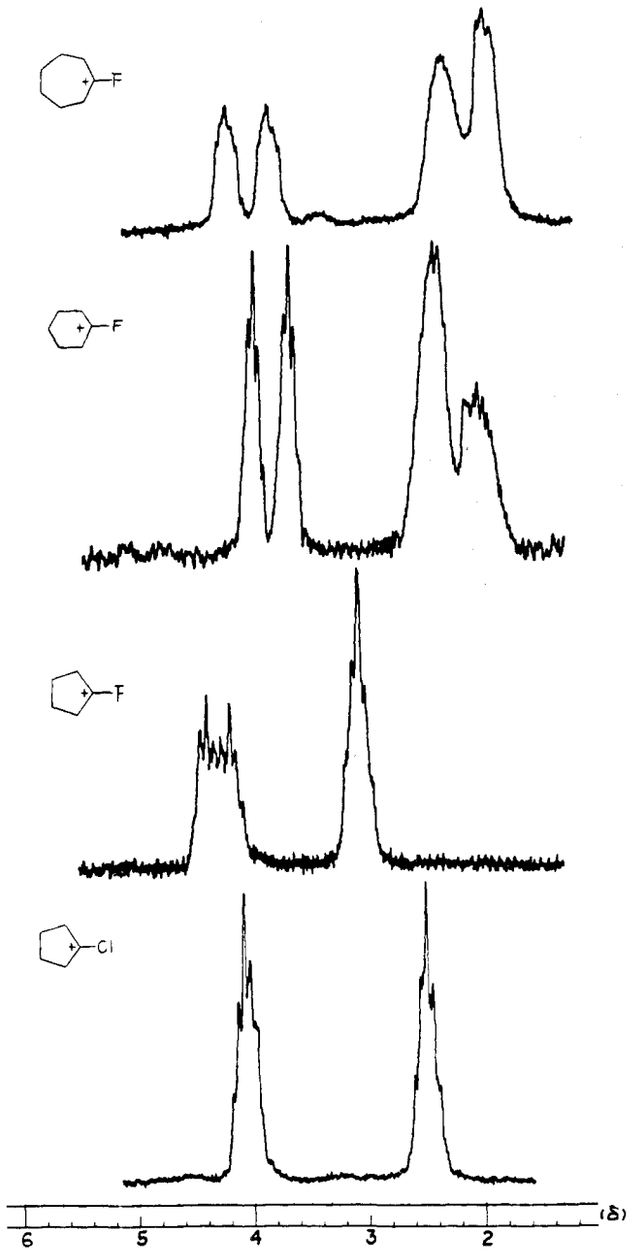
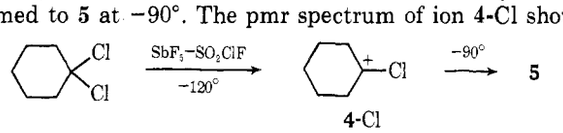


Figure 1. Pmr spectra of 1-fluoro(chloro)-1-cycloalkyl cations (60 MHz).

−78°, only the methylcyclopentenyl cation **5** was observed.) Ion **4**-Cl was not stable and was slowly transformed to **5** at −90°. The pmr spectrum of ion **4**-Cl shows

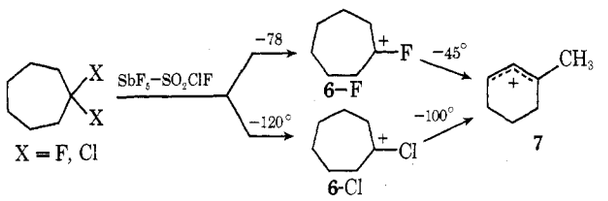


4-Cl

proton absorption at δ 4.25, 3.00, and 2.21 for α-CH_3 (4 protons), β-CH_2 (4 protons), and γ-CH_2 (2 protons), respectively (Table I).

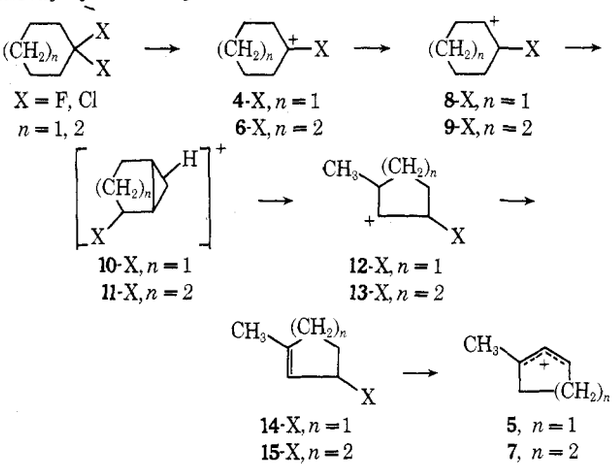
The great differences in stability between ions **4**-Cl and **4**-F as well as between **1**-Cl and **1**-F are interesting and will be discussed subsequently.

1-Halo-1-cycloheptyl Cations. The 1-halo-1-cycloheptyl cations **6**-F and **6**-Cl were prepared from 1,1-difluoro- and 1,1-dichlorocycloheptane, respectively, in SbF_5–SO_2ClF solution. Ion **6**-Cl can only be prepared at −120°. It is extremely unstable and rapidly transforms to the methylcyclohexenyl cation **7** at −100°. The 1-fluoro-1-cycloheptyl cation **6**-F, however, could be prepared at −78° without rearrangement. Ion **6**-F also slowly trans-



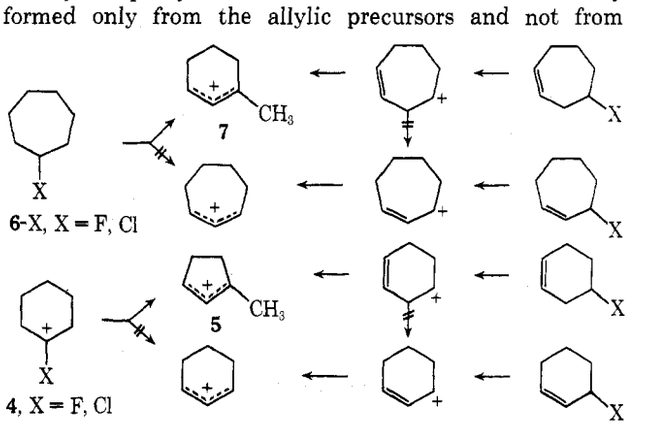
forms to **7** at −45° (5 min). The pmr spectrum of **7** is shown in Figure 1.

The transformation of both **4**-F and **4**-Cl to the methylcyclopentenyl cation **5** as well as ions **6**-F and **6**-Cl to the methylcyclohexenyl cation **7** is of mechanistic interest.[9]



1,2-Hydrogen shifts in cations **4**-F and **4**-Cl to **8**-Cl are likely to occur, since *trans*-1,2-dihalocyclohexanes also give the 1-methylcyclopentenyl cation **5** when treated with SbF_5–SO_2ClF solution under similar conditions.[8] Ring contraction may involve protonated cyclopropane intermediates (**10**-X) which subsequently will lead to ions **12**-X. Proton elimination of **12**-X to **14**-X is considered to be favorable. Ionization of **14**-X with SbF_5–SO_2ClF (SO_2) solution is a known process.[8]

Cyclohexenyl and cycloheptenyl cations have been shown to be stable under these reaction conditions studied.[8,9] It is surprising that the ring contraction reaction is faster than the formation of allylic cations. Cyclohexenyl and cycloheptenyl cations have been shown to be directly formed only from the allylic precursors and not from



homoallylic precursors.[1b,9] Ring contraction (path b) of **16** and **17** to **5** and **7**, respectively, must take place prior to intramolecular hydrogen shift (path a).[9]

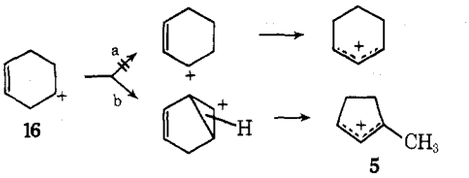


Table I
^{1}H and ^{19}F Nmr Parameters of Halocarbenium Ions

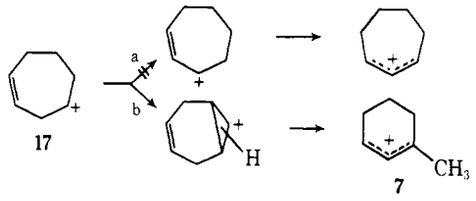
Cation	Solvent[a]	Hα[b]	Hβ[b]	Hγ[b]	ϕ[c]	J_{HF}[d]
1-Cl	A	4.40	2.98			
	B	4.05	2.50			
1-F[e]	A	4.25	3.04		−149.4, q	12
	B	3.92	2.54			
4-Cl	A, −105°	4.25	3.00	2.20		
4-F[e]	A	4.10	2.82	2.50	−166.5, q	20
	B	3.95	2.38	2.10		
6-Cl	A, −105°	4.30	3.15	2.35		
6-F[e]	A	4.34	2.65	2.38	−160.6, q	22
	B	4.07	2.30	1.85		
18-Cl	A	4.38				
18-F[e]	A	4.63			−185, h	26
19-F[e]	A	4.65 (CH_2)	1.98 (CH_3)		−183.5, m	24
		4.10 (CH_3)				26
20-F[e]	A	4.45	1.90		−173.7, q	24
21-F[e]	A	4.20	3.45	2.70	−126.4, t	17

[a] A, SbF_5–SO_2ClF; B, SbF_5–SO_2. Ions were measured at −80° unless otherwise indicated. [b] Pmr chemical shifts (δ) are given in parts per million from capillary tetramethylsilane. [c] ^{19}F chemical shifts are given in parts per million from capillary CCl_3F: q, quentet; h, heptet; m, multiplet; and t, triplet. [d] In hertz. [e] ^{1}H chemical shifts of α-H in fluorocarbenium ions are usually observed as doublet multiplets. Only averaged chemical shifts are given. Coupling constants [$J(H_\alpha F)$] are shown in the last column.

Table II
Carbon-13 Nmr Parameters of Halocarbenium Ions[a]

Cation	C$^+$	C$_\alpha$	$\Delta\delta_1$[c]	C$_\beta$	$\Delta\delta_2$[c]	C$_\gamma$	C$_\delta$	J_{CF}[d]
1-Cl	316.3	65.9	15.9	27.9	38			
1-F	294.0[b]	50.0		27.4	25.6			439.2
4-Cl	318.6	68.7	20.6	29.4	39.3	22.3		
4-F	285.3[b]	48.1		29.4	28.7	23.4		424.8
6-Cl	319.3	70.3	19.5	28.5	41.8	23.9		
6-F	287.2[b]	50.8		28.8	22.0	25.6		427.7
18-Cl	313.7	50.5	13.3					
18-F	282.8[b]	37.2						420.0
19-F	283.6[b]	47.5 (CH_2)		5.8				421.0
		34.5 (CH_3)						
20-F	285.0[b]	46.5		6.1				429.1
21-F	301.6[b]	56.1		53.9	2.2	29.3	36.4	422.6

[a] ^{13}C chemical shifts [$\delta(^{13}C)$] are given in parts per million from capillary TMS. Ions were measured according to the conditions given in Table I. [b] Carbenium carbon shifts in fluorocarbenium ions are usually observed as doublets with coupling constants (J_{CF}) shown in the last column. Averaged ^{13}C chemical shifts are therefore given. [c] $\Delta\delta_1 = \delta(^{13}C_\alpha)$ (in chlorocarbenium ions $- \delta(^{13}C_\alpha)$ (in fluorocarbenium, ions). $\Delta\delta_2 = \delta(^{13}C_\alpha) - \delta(^{13}C_\beta)$. [d] In hertz.



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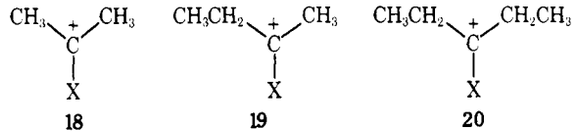

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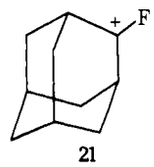

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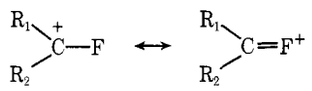
Nuclear Magnetic Resonance Spectroscopic Studies. Table I summarizes the proton nmr parameters of the studied 1-halo-1-cycloalkyl cations. We also have obtained ^{19}F nmr parameters of the ions, as shown in Table I, along with those of the model ions (18–21). Solvent dependency of the chemical shifts was noticed when ions were prepared in different acid systems. Protons α to the carbenium ion center in chlorocarbenium ions are generally more deshielded than those in fluorocarbenium ions, indicating that more positive charge is shared by the fluorine atom than by the chlorine atom. Fluorine shifts in cyclic fluorocarbenium ions are generally less deshielded than those in acyclic fluorocarbenium ions. This indicates that fluorine back-donation is less substantial in cyclic than in acyclic fluorocarbenium ions. Large deshielding of ^{19}F shifts observed in fluorocarbenium ions indeed strongly implies that significant charge delocalization unto fluorine occurred. It is generally believed to be due to π-donation by the fluorine lone pairs of electrons into the cationic center. We have also prepared the geometrically rigid 2-fluoro-2-adamantyl cation **21**, which gives a less deshielded fluorine nmr shift (ϕ −126.4), indicating that fluorine back-donation is more feasible in conformationality mobile systems than in conformationally rigid systems. The extent of fluorine back-donation is therefore dependent on the molecular conformation.

An even better indication of the differing degree of back-donation in halocarbenium ions is revealed by the ^{13}C chemical shifts of the ions. Table II summarizes cmr parameters of the studied cyclic halorocarbenium ions and several model ions. Carbenium carbon shifts in fluorocarbenium ions are found to be about 20 ppm deshielded from those corresponding chloro analogs. Owing to the substantial contribution of the resonance forms involving stronger fluorine back-donation, carbons α to the carben-



ium ion center in fluorocarbenium ions should experience less inductive deshielding effect than those in chlorocarbenium ions. This indeed is found to be the case as α carbon shifts in chlorocarbenium ions are about 13–20 ppm more deshielded than those in fluorocarbenium ions ($\Delta\delta_1$ in Table II). It is also found that carbon shift differences ($\Delta\delta_2$) between α and β carbons in chlorocarbenium ions are about 10–20 ppm larger than those in fluorocarbenium ions.

The conformational dependency of fluorine back-donation is also revealed from ^{13}C chemical shifts of carbenium ion centers, which in acyclic fluorocarbenium ions are less deshielded than those in the cyclic analogs. A lesser degree of fluorine back-donation should correspond to more deshielded carbenium carbon shifts, since in this case less positive charge should be shared by the fluorine atoms.

Halogen "back-donation" has been demonstrated previously by comparing the carbon-13 shifts of dimethylhalocarbenium ions and a series of haloolefins.[4d] For comparison we have now also reinvestigated the carbon-13 shifts of dimethylhalocarbenium ions by the Fourier transform method and data are included in Table II. The carbenium carbon shift of dimethylfluorocarbenium ion is found to be $\delta(^{13}C)$ 282.8 (In our quoted paper, owing to a computation error, a value of 345 was reported by the INDOR method. The recalculated value is in good agreement with the Fourier transform result.)[4e] The data for $(CH_3)_2C^+F$ and $(CH_3)_2{}^+CCl$ further substantiate the importance of fluorine "back-donation." Thus, without comparing the differences in carbon-13 shifts $[\Delta\delta(^{13}C)]$ between halocarbenium ions and their corresponding olefins, the shielding of the carbenium carbon shift of $(CH_3)_2C^+F$ is a good indication of substantial charge being delocalized unto the fluorine through 2p–2p interaction. This is also in good agreement with the observed deshielded fluorine shift at ϕ −181.91 for $(CH_3)_2C^+F$.[4d]

Although steric and inductive effects may affect the ^{19}F chemical shifts, they cannot be the dominating factors which result in the observed variation for cyclic, acyclic, and polycyclic fluorocarbenium ions. ^{19}F nmr chemical shifts for the conformationally most rigid fluorocarbenium ions appear the least deshielded and those of the less rigid systems appear the most deshielded. Fluorine shifts of conformationally labile systems appear inbetween. These observations are in accord with the recent experimental results reported by Farnum and Patton[10] of the ^{19}F nmr parameters of a series of tertiary *p*-fluorophenylcarbenium ions in terms of steric restriction of rotation by solvation. They also have found that the ^{19}F chemical shifts fall into three main groups: acyclic fluorinated carbenium ions at lowest field, monocyclic at intermediate field, and bicyclic at highest field. The total range of 8 ppm represents about 6 kcal energy difference in stability. For the presently studied fluorocarbenium ions, a range of 57 ppm is observed.

From Table II it also can be seen that J_{CF} values of fluorocarbenium ions are unusually large (>400 Hz). The large J_{CF} values also correspond to the deshielded ^{19}F chemical shifts.[11] Although J_{CF} values generally vary widely depending on their environment, there are three major factors contributing to J_{CF}, *i.e.*, the extent of π-bond formation and the ionic character of the C–F bond, as well as the s character of the carbon orbital in the C–F bond. J_{CF} usually increases in magnitude with decreasing ionic character, decreasing s character, and increasing π-bond formation. J_{CF} values given in Table II for cyclic, acyclic, and polycyclic fluorocarbenium ions do not show substantial variation with the exception of the 1-fluorocyclopentyl cation, which also shows a more deshielded carbenium ^{13}C chemical shift. A consistent explanation of the fluorine back-donation unto the large J_{CF} values cannot be given at the present time. The greater extent of π-bond formation and the decrease of ionic character might be the major factors for larger J_{CF} values observed in fluorocarbenium ions.

Conclusions

The study of 1-halo-1-cycloalkylcarbenium ions shows that halogen "back-donation" as well as configuration (ring size) are the two most important factors affecting their stability. Owing to the better 2p–2p interaction in fluorocarbenium ions, we have previously shown that the degree of halogen "back-donation" is in the order F > Cl > Br. Our present data show good agreement with this order. 1-Bromo-1-cycloalkylcarbenium ions could even not be directly observed. For example, the 1-bromo-1-cyclopentyl cation was not stable even at −120° and immediately was transformed to the cyclopentenyl cation. This result enhances our previous conclusion that bromine "back-donation" is not significant in bromocarbenium ions. Indeed, bromine destabilizes carbenium ion through its obvious inductive effect. The different rate of transformation of 1-halo-1-cyclohexyl cations (**4**-F and **4**-Cl) into the 1-methyl-1-cyclopentenyl cation (**5**), on the other hand, clearly suggests that fluorine "back-donation" is more significant than that of chlorine.

Experimental Section

Materials. 1,1-Dichlorocyclopropane, -butane, and -pentane, 1,2-dichlorocyclopentane, and 1,1-difluorocyclohexane were obtained from either K & K Laboratories or Aldrich Chemical Co. 1,1-Difluorocyclopentane[12a] and -cycloheptane[12b] and 2,2-difluoroadamantane[12b] were prepared from the corresponding ketones with SF_4 according to literature procedures. 1,1-Dichlorocyclohexane and -heptane were prepared by reaction of the corresponding ketones with PCl_3–PCl_5.

Antimony pentafluoride and fluorosulfuric acid were purified as previously described.[13] The purified reagents were stored in Teflon bottles.

Nuclear Magnetic Resonance Spectra. Proton and fluorine nmr spectra were obtained on a Varian Model A56/60A nmr spectrometer equipped with a variable-temperature probe. External (capillary) TMS and $CFCl_3$ were used as references for ^1H and ^{19}F spectra, respectively. Carbon-13 nuclear magnetic resonance spectra were obtained by the Fourier transform method using a Varian XL-100 nmr spectrometer equipped with a variable-temperature probe. Carbon shifts are referred to capillary TMS.

Preparation of Ions. The procedure for the preparation of cyclic halocarbenium ion is essentially the same as that previously reported.[8,9]

Acknowledgment. Support of our work by the National Science Foundation is gratefully acknowledged.

Registry No.—**1**-Cl, 51608-49-2; **1**-F, 51608-50-5; **4**-Cl, 51608-51-6; **4**-F, 51608-52-7; **6**-Cl, 51608-53-8; **6**-F, 51608-54-9; **18**-Cl, 24154-14-1; **18**-F, 14665-81-7; **19**-F, 51608-55-0; **20**-F, 51608-56-1; **21**-F, 51608-57-2.

References and Notes

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(2) Taken in part from the Ph.D. Thesis of G. Liang, Case Western Reserve University, 1973.
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Positional Reactivities and Mechanisms of Deuteration of 1-Methylimidazole in pD and $-D_0$ Regions. Reinvestigation of the Kinetics of 2-Hydrogen Exchange in Imidazole

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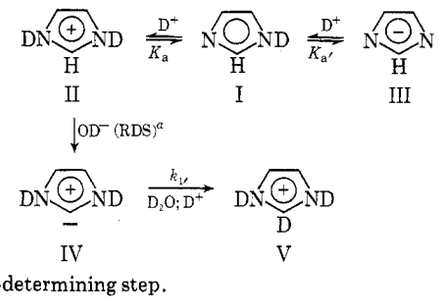
Of the rate equations 1–4 for 2-deuteration of imidazole *via* the ylide mechanism involving the OD^-, the imidazole free base, its conjugate anion, and D_2O, respectively, the experimental pD–rate profile conforms uniquely to eq 1. Rate expressions for the deuteration of the three ring sites in 1-methylimidazole by way of four independent routes are also presented (eq IIa–d). Successive exchanges of the three ring hydrogens were studied in D_2O as a function of the medium acidity. In the region of pD 0–13, the profiles for the 2-, 4-, and 5-hydrogen exchange are similar and as predicted by eq IIb. At pD > 13, eq IIa contributes significantly to the reaction at the 2 and 4 position. In strong acids, the rate of deuteration of all the ring positions increased fairly linearly with acidity as required by eq IId. Similar deuteration of 1,3-dimethylimidazolium iodide substantiates the above. These findings also allow the determination of the theoretical second-order rate constants which provide a quantitative account of the intrinsic reactivity of the 2, 4, and 5 position of 1-methylimidazole in undergoing deuteration. The relative rates are 54,500:1.6:1, respectively, *via* the ylide mechanism and 1:73:120, respectively, *via* the SEAr pathway involving the conjugate acid species.

The imidazole ring system has achieved textbook status because many substances of biological and chemical interest, both natural and synthetic, are imidazoles. Although there are many electrophilic substitution reactions of imidazoles known in the literature,[1] including, in some instances, kinetic analysis of a particular product, no quantitative data are as yet available for comparing the positional reactivities of the three potentially different carbon positions of the imidazole ring in any particular reaction. To this end 1-methylimidazole, the simplest model which possesses three unique ring positions, *viz.*, the C-5 position adjacent to a pyrrole nitrogen atom, C-4 to a pyridine nitrogen, and C-2 to both, was chosen for the present study of the reactive character of these three sites. Since typical aromatic substitutions,[1] *e.g.*, nitration, sulfonation, and halogenation, have invariably yielded a single product, they are unsuitable for a comparative study of positional reactivity. We, therefore, decided on the deuteration reaction for a comprehensive kinetic investigation. On account of what is known about the two general mechanisms of deuteration of heterocycles, *viz.*, one that proceeds *via* electrophilic aromatic substitution[2] and another *via* ionization of the carbon–hydrogen bond,[3] it is predictable that both of these pathways may be operative in the deuteration of 1-methylimidazole depending on medium acidity. This article details the kinetics and mechanisms of successive isotopic exchanges of the three ring hydrogens, and the derivation of the theoretical constants for the rate-determining steps which involve either a Wheland or an ylide intermediate. These rate constants allow the first quantitative comparison of the positional reactivities of this ring system, and may well be applicable to predicting or interpreting the orientation of other substitution reactions involving similar intermediates.

Results and Discussion

2-Deuteration of Imidazole. Consideration of General Acid and General Base Catalysis. The most general mechanism[3] of hydrogen–deuterium exchange in azoles and azolium systems involving an ylide intermediate is shown in Scheme I for the deuteration of imidazole at the

Scheme I



[a] Rate-determining step.

2 position. By analogy to the rate expression derived for thiazole exchange,[3a] the observed pseudo-first-order rate constant for imidazole 2-deuteration is given by eq 1,