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EXPERIMENTAL DETERMINATION OF CARBON vs. OXYGEN REGIOSELECTIVITY IN REACTIONS OF GAS-PHASE ENOLATE IONS

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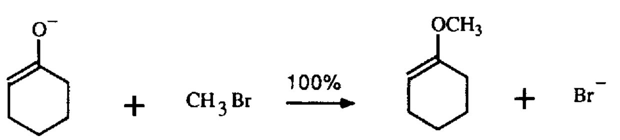
ABSTRACT

A gas-phase experimental investigation of the competition between carbon and oxygen alkylation of a series of cyclic and acyclic enolate ions is described. Perfluoropropylene is shown to react in a characteristic way with oxyanions and carbanions to produce distinctive ionic products. The relative yields of these products formed in reactions with ambident enolate ions provides a measure of their intrinsic carbon vs. oxygen regioselectivity. The results for a series of enolates derived from aldehydes, ketones, esters, amides and related compounds show a wide range of reactivity which is a function of the nature of the central substituent. Most aldehyde and ketone enolates react mainly through oxygen, while enolates with σ-acceptor of π-donor type central substituents react mainly through carbon. Ring-size in cyclic ketone enolates also influences C vs. O regioselectivity, i.e. small-ring enolates react mainly through carbon, while larger ring enolates (C_7–C_9) react preferentially through oxygen. The enolate reactivity patterns can be generally accounted for by the keto–enol energy differences for the parent carbonyl compounds, although some exceptions are evident. The origins of the highly variable, kinetically determined regioselectivities are discussed.

INTRODUCTION

Enolate ions are among the most important intermediates in synthetic organic chemistry. Considerable effort has been devoted to controlling the carbon vs. oxygen regioselectivity and the stereoselectivity in reactions of these ambident ions with alkylating agents.[1] The main emphasis in the majority of studies has been on steric-approach control, the influence of the electrophile, and on the effects of solvent, counter-ions and sequestering agents. There have been fewer systematic studies of the intrinsic properties of the enolate ions themselves which may affect C vs. O alkylation preferences.[2] Recently, Ellison and co-workers reported the remarkable result that cyclohexanone enolate ion reacts with CH_3Br *in the gas phase* to produce exclusively the neutral vinyl ether product from kinetic O-alkylation, equation (1).[3]



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Subsequent computational studies of the hypothetical reaction between CH_3F and acetaldehyde enolate by Houk and Paddon-Row led to the conclusion that O-alkylation was kinetically favored since the calculated transition state was 3–9 kcal/mol lower than that for the thermodynamically favored C-alkylation pathway.[4] In contrast, Bartmess reported significant contributions from C-alkylation in gas-phase Claisen condensations involving enolate ions and neutral esters.[5]

In the course of our own studies of gas-phase carbanion chemistry using the flowing afterglow technique, we recently discovered a convenient chemical method for interrogating the carbon vs. oxygen reactivity preferences of certain enolate ions. Inspired by Ellison's elegant experiment and curious about the generality of the result, we have applied our regiochemical probe to a variety of cyclic and acyclic enolate ions. The results of these studies show that the nature of the central substituent in acyclic enolate ions and the ring size in cyclic systems can exert a significant influence on their kinetically determined C/O reactivity ratios in the gas phase.

EXPERIMENTAL SECTION

Most of the experiments were carried out with use of a flowing afterglow apparatus which has been fully described previously.[6] Unless stated otherwise, the standard conditions in the helium flow reactor were $P(\mathrm{He}) = 0{\cdot}40$ torr, $v(\mathrm{He}) = 9600\,\mathrm{cm/s}$ and $T = 298 \pm 2\,\mathrm{K}$. Most of the negative ion reactants were generated from the corresponding conjugate acid by proton abstraction with either OH^- (PA = 390·7 kcal/mol)[7] or NH_2^- (PA = 403·6 kcal/mol).[7] Hydroxide ion was produced from addition of a mixture of N_2O and CH_4 to the electron impact source, and amide ion was generated by electron impact ionization of ammonia. Ethoxide ($C_2H_5O^-$), *t*-butoxide (*t*-$C_4H_9O^-$), and acetate ($CH_3CO_2^-$) anions were produced by reaction of OH^- with diethyl ether, di-*t*-butylperoxide, and acetic anhydride, respectively. The hydroperoxy anion (HOO^-) was produced by reduction of molecular oxygen by deprotonated 1,3-cyclohexadiene ($C_6H_7^-$).[8] Each of the enolates could be prepared by proton transfer from the parent carbonyl compound to OH^- or NH_2^-. When homoconjugate cluster ion formation was problematic (as in the case of the aldehydes) lower flows of the neutral reagents were used and phenetole ($PhOCH_2CH_3$) was added to attenuate the residual OH^- by an elimination reaction to form the unreactive phenoxide ion ($C_6H_5O^-$). In order to avoid uncertainty regarding the site of proton abstraction with 3-butenone, $CH_2{=}CHCOCH_3$, an 'authentic' enolate ion corresponding to abstraction at C-1 ($CH_2{=}CHCOCH_2^-$) was prepared by NH_2^--initiated desilylation of the corresponding trimethylsilylenol ether, $CH_2{=}CHC(OSiMe_3)CH_3$.[9] The reactivity of the ion produced in this way and by proton abstraction did not differ, indicating that abstraction of a proton from 3-butenone occurs predominantly at the C-1 position.

Primary product distributions for reactions between negative ions and $CF_2{=}CFCF_3$ were determined by monitoring the observed product ion abundances at low and high conversions of the reactant anion. Plots of the normalized product ratios versus C_3F_6 flow rate or percentage reactant ion conversion for several enolate ions show that secondary reactions between C_3F_6 and the primary product ions are usually absent.[10] Thus, the product ion abundances obtained from a single mass spectrum at low conversions of the reactant ion represent a satisfactory measure of the branching ratio for the reaction. The reported product ion percentages are estimated to be accurate to within ±10%; with typical precision better than ±5%. The mass spectrometer was operated with the lowest practical resolution and a consistent set of lens potentials in order to minimize mass discrimination. In order to standardize the detection system prior to each day's experiments, the reaction of OH^- with C_3F_6 was initiated with the neutral reagent located at a distance of 23 cm from the mass spectrometer sampling orifice. Sufficient C_3F_6 is added to react away most of the initial OH^-, and the detector tuning is adjusted so that the lowest mass primary product ion F^- (*m/z* 19) and the highest mass secondary product ion $C_6F_{13}^-$ (*m/z* 319) are in a ratio of 1:10.*

Kinetics measurements were made by the variable reaction distance method with use of a moveable reagent inlet.[12] Bimolecular rate coefficients measured with our instrument have an estimated accuracy of ±20% and a typical precision of ±5%.[6]

During the latter stages of this study, an Extrel triple quadrupole analyzer was incorporated into the instrument, and some of the results described in this paper were obtained with the new apparatus. Briefly, the triple quadrupole analyzer consists of three coaxially aligned quadrupoles, with the first (Q1) and third (Q3) units operable in mass resolving mode, and the middle quadrupole (Q2) serving as a focusing collision cell by operation in 'rf-only' mode.[13] Q2 is a gas-tight quadrupole, and may contain up to a few millitorr of an inert target gas such as argon, or reactive neutral reagents.[14] The axial kinetic energy of an ion selected from the flow reactor by Q1 may be varied over a range of <1 eV to 150 eV. For the present study the triple quadrupole analyzer was operated in the daughter-ion mode (Q1 mass fixed; Q3 mass scanning) for obtaining collision-induced dissociation (CID) spectra of selected ions with argon collision gas, or for examining bimolecular reactions of certain negative ions with C_3F_6 in Q2 at low kinetic energies (<1 eV lab).

Gas purities were as follows: He (99·995%), Ar (99·995%), N_2O (99·0%), CH_4 (99·5%), NH_3 (99·99%), $CF_2{=}CFCF_3$ (99·5%), $CH_2{=}CHCH_3$ (99·0%), and $CH_2{=}C(Me)CH_3$ (99·9%). The liquid reagents and volatile solids were obtained commercially and used without further purification, except for degassing just prior to use. In almost all cases, the mass spectra resulting from reaction of these compounds with OH^- and/or NH_2^- showed no significant ionizable impurities that might interfere with the C_3F_6 analyses.

RESULTS AND DISCUSSION

A wide variety of enolate ions of ketones, aldehydes, esters, amides, etc. can be generated in the gas phase by proton abstraction from the parent compound or by fluorodesilylation of an appropriate trimethylsilyl derivative.[9] Since alkylation of these ions with the usual electrophiles such as methyl halides results in a neutral organic product, neutral collection techniques are necessary to evaluate the C/O alkylation ratio in the products because only charged species are directly detected in most gas-phase ion/molecule reaction experiments. This is precisely how Ellison and co-workers determined that the enol ether was the exclusive neutral product of reaction (1).[3] While neutral product analysis provides the information which is most directly relevant to the corresponding alkylation reaction taking place in solution, it requires painstaking care in identifying the ion/molecule reaction products, a means for distinguishing these products from possible neutral/neutral reactions, and a highly sensitive detector for the minuscule amount of product which can be collected from the reactor.[3]

In would be desirable to have a chemical method for evaluating C/O regiochemical preferences of enolate ions which involves the more straightforward analysis of ionic products.

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*The flow rate of C_3F_6 required to achieve this product ratio is $1{\cdot}2 \times 10^{-2}$ STP cm^3/sec, corresponding to a concentration of $8{\cdot}0 \times 10^{11}$ molecules/cm^3. This is in good agreement with the results of Su *et al.*[11]

An ideal reagent for this approach would be one which reacts rapidly and completely with a wide variety of enolate ions to yield distinct ionic products depending upon whether reaction occurred at carbon or at oxygen.

Recently, Nibbering and co-workers described the rich gas-phase reactivity exhibited by polyfluorinated aromatic and olefinic compounds such as pentafluoroanisole, perfluorobenzene and tetrafluoroethylene in the presence of various negative ions in an ion cyclotron resonance (ICR) spectrometer.[15] Certain of the reactions that were reported in these studies and in earlier ICR investigations by Riveros[16] and Beauchamp[17] suggested to us that an unsaturated, polyfluorinated reagent might satisfy the requirements specified above for a chemical probe of carbon vs. oxygen reactivity in ambident ions.

We have found the perfluoropropylene $CF_2{=}CFCF_3$ does indeed provide the desired reactivity patterns, and in the following sections we outline the principles of its use in determining C/O reactivity ratios for gas-phase enolate ions. The protocol is to first establish the distinct products, scope, and mechanisms of perfluoropropylene reactions with pure oxyanions and pure carbanions, and then use this information in interpreting the outcome for reactions involving ambident enolate ions that possess both oxygen and carbon charge-bearing sites.

REACTIONS WITH OXYANIONS: O$^-$/F EXCHANGE

The general reaction of C_3F_6 with oxyanion nucleophiles is illustrated by the results for OH^-, alkoxide ions (RO^-) and carboxylates (RCO_2^-) shown in the upper part of Table 1. These ions span a range of more than 50 kcal/mol in their proton affinities,[7] and involve both localized and delocalized negative charges which reside exclusively on oxygen. Hydroxide ion reacts rapidly with C_3F_6 ($k = 1{\cdot}3 \times 10^{-9}$ cm^3/s) to yield two ionic products, equation (2).

$$\begin{aligned} HO^- + CF_2{=}CFCF_3 &\xrightarrow{95\%} C_3F_5O^- + HF \\ &\xrightarrow{5\%} C_3F_5OH + F^- \end{aligned} \qquad (2)$$

Table 1. Reactions of oxyanions and carbanions with $CF_2{=}CFCF_3$, 0·4 torr, 298 ± 2 K

Anion	$C_3F_5O^-$(%) *O^-/F exchange*	$[M + C_3F_6 - n\text{HF}]^-$(%)				
		F^-	$n = 0$	$n = 1$	$n = 2$	$n = 3$
HO^-	95	5				
CH_3O^-	99	1				
$CH_3CH_2O^-$	100					
$(CH_3)_3CO^-$	100					
$CH_3CO_2^-$	100					
HOO^{-a}	76		11			
$C_6H_5^-$		96		4		
$CH_2{=}CHCH_2^-$					95	5
$CH_2{=}C(Me)CH_2^-$					99	1
$PhCH_2^-$				2	98	
$NCCH_2^-$			1	32	67	

[a] An additional product at *m/z* 166 ($C_3F_6O^-$) is observed (13%)

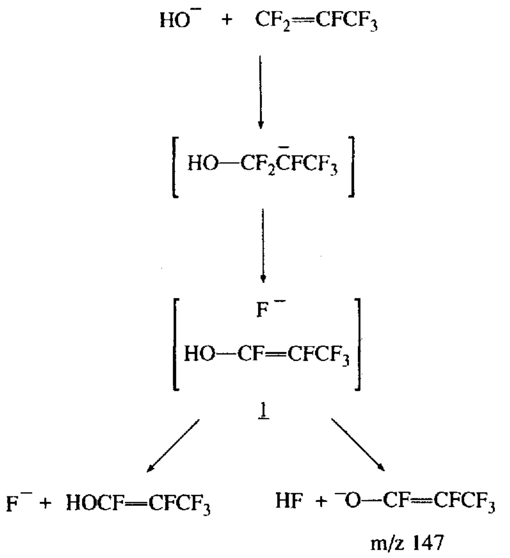
With higher C_3F_6 flow rates, secondary products at *m/z* 169 ($C_3F_7^-$) and *m/z* 319 ($C_6F_{13}^-$) appear, corresponding to reaction of F^- with one and two additional C_3F_6 molecules, respectively.

Nibbering and co-workers have emphasized the importance of F^- ion/molecule complexes as intermediates in nucleophilic substitution reactions involving polyfluorinated aromatic compounds,[15] and it is likely that such intermediates also play a role in perfluoropropylene reactions. Accordingly, the addition–elimination mechanism shown in Scheme 1 is proposed for reaction (2). Initial attack by the nucleophile at the terminal position of the electron-deficient double bond is followed by elimination of F^- to produce the perfluoroenol complex **1**. The F^--ion/molecule complex may dissociate directly, or first undergo proton transfer to yield HF and the perfluoroenolate ion. The alternative methanism involving OH^- addition to the 2-position of $CF_2{=}CFCF_3$ followed by HF loss to form $F_3C(O)CF_2^-$ (instead of CF_3CFCFO^-) is ruled out by the fact that the $C_3F_5O^-$ product ion of reaction (2) undergoes CID in the triple quadrupole to yield CF_3^- (*m/z* 69, 66%), $C_2F_3^-$ (*m/z* 81, 21%) and F^- (*m/z* 19, 13%), while an authentic $CF_3C(O)CF_2^-$ ion (generated from reaction of NH_2^- with $CF_3CH(OH)CF_3$) fragments under identical conditions to yield only CF_3^-. In addition, perfluoropropylene is known to undergo nucleophilic addition preferentially at the terminal position in solution.[18] It is perhaps instructive to view the reaction shown in Scheme 1 (and any like it) as a formal exchange of the isoelectronic O^- ion and F-atom.

Alkoxide ions also yield $C_3F_5O^-$ as the major or, in some cases, exclusive ionic product from reaction with C_3F_6. For example, CH_3O^- reacts rapidly ($k = 1{\cdot}1 \times 10^{-9}$ cm^3/s) to yield nearly 100% $C_3F_5O^-$ and a trace of F^- equation (3). Methyl fluoride

$$CH_3O^- + CF_2{=}CFCF_3 \longrightarrow CH_3F + C_3F_5O^- \tag{3}$$

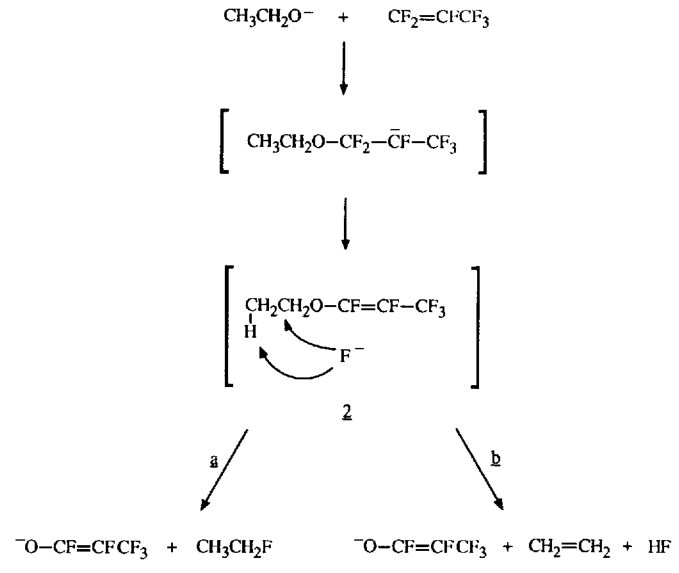
is the only sensible neutral product for reaction (3). It can be readily accounted for by a mechanism similar to the one shown in Scheme 1, but with a nucleophilic displacement of $C_3F_5O^-$ from the enol ether by F^- instead of a proton transfer as the final step. With larger



Scheme 1

alkoxide ions such as EtO^- and t-BuO^-, $C_3F_5O^-$ is the only ionic product observed. In these reactions, the neutral products could be either the corresponding alkyl fluoride, formed by the O^-/F exchange mechanism described above, or an olefin plus HF that may arise from a β-elimination reaction within an F^-/enol ether complex. Scheme 2 illustrates these alternatives for the $CH_3CH_2O^-$ reaction. Path **a** is the more exothermic decomposition route for the intermediate F^-/enol ether complex **2** by 10 kcal/mol,* however the overall free energies of the two channels are comparable.

A direct analogy may be drawn between the behavior of alkoxide ions with C_3F_6 and their reported behavior with other polyfluorinated compounds that have been examined previously. Riveros observed an analogous fluoroenolate product ion, $CH_2{=}CFO^-$, from reactions of RO^- ($R = CH_3$, CD_3, C_2H_5, C_2D_5, i-C_3H_7) with CH_2CF_2 in an ICR.[16] Based on the apparent insensitivity of the rates of these reactions to the size of the alkyl group, Riveros suggested that a preference exists for displacement rather than β-elimination as the main decomposition mechanism for the intermediate $F^-/RO{-}CF{=}CF_2$ complexes. However, in their studies of the gas-phase reactions between aliphatic alkoxide ions and $CF_2{=}CF_2$, Sullivan and Beauchamp favored the occurrence of *both* S_N2 displacement and β-elimination mechanisms since the overall rates were observed to increase with increasing numbers of β-hydrogens in the alkoxide ion (with the exception of t-BuO^-).[17] Similarly, Nibbering and co-workers concluded that elimination was the favored mechanism for formation of the fluorinated phenoxide ion, $CH_3OC_6F_4O^-$, in reactions between alkoxide ions and pentafluoroanisole, $CH_3OC_6F_5$, since it was found that blocking the β-position of the alkoxide, as in $(CH_3)_3CCH_2O^-$, results in the dissappearance of $CH_3OC_6F_4O^-$ from the product ion mixture.[15b]



Scheme 2

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*$\Delta H_f(C_3F_6) = -266$ kcal/mol[19]; $\Delta H_f(C_3F_5O^-) = -341$ kcal/mol, based on $\Delta H_f(CF_3CHFC(O)F) = -304$ kcal/mol[20] and an estimated acidity for this compound of 328 kcal/mol. All other heats of formation taken from reference 21. ΔH_{rxn} (path a) $= -93$ kcal/mol; ΔH_{rxn} (path b) $= -84$ kcal/mol.

Carboxylate ions such as $CH_3CO_2^-$ also react with C_3F_6 to produce exclusively $C_3F_5O^-$, equation (4). As with the alkoxide ions,

$$CH_3CO_2^- + CF_2{=}CFCF_3 \xrightarrow{100\%} C_3F_5O^- + CH_3COF \text{ or } HF + CH{=}C{=}O \tag{4}$$

two likely options exist for the neutral product(s) accompanying $C_3F_5O^-$ formation: acetyl fluoride or ketene plus HF. Here, an elimination (E2) reaction may compete with a nucleophilic acyl substitution ($B_{AC}2$) in the formation of $C_3F_5O^-$, equation (4). Both reaction routes are strongly exothermic.* We favor the elimination mechanism for this reaction since it has been shown that $B_{AC}2$ mechanisms are relatively slow compared to ketene-elimination in *bimolecular* gas-phase reactions of negative ions with carbonyl compounds possessing alpha-hydrogens.[22]

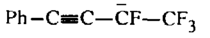
From the consistent reactivity pattern described above, we assign the $C_3F_5O^-$ ion as the characteristic product of reactions between oxyanion nucleophiles and C_3F_6. Its appearance in reactions with ambident enolate ions will be construed as an indication of initial reaction at the oxygen end.

REACTIONS WITH CARBANIONS: CONDENSATION

We have chosen allyl anion ($CH_2CHCH_2^-$), isobutenyl anion ($CH_2C(Me)CH_2^-$), benzyl anion ($PhCH_2^-$), phenide ($C_6H_5^-$) and cyanomethyl anion ($NCCH_2^-$) as representative cases for evaluating the reactivity of C_3F_6 with pure carbanions. The general reaction observed in each case is condensation involving the addition of C_3F_6 to the carbanion followed by loss of one or more HF molecules. As shown in the lower part of Table 1, addition with loss of two HF molecules dominates for most carbanions, while for phenide ion ($C_6H_5^-$), F^- is the major product. Each of these reactions occur rapidly. The measured rate coefficients for the reactions of C_3F_6 with allyl ion and benzyl ion are $8{\cdot}9 \times 10^{-10}$ cm^3/s and $6{\cdot}3 \times 10^{-10}$ cm^3/s, respectively.

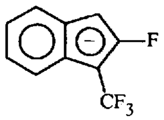
Our view of the mechanism for the C_3F_6 reaction with allyl anion is shown in Scheme 3. Initial attack by the carbanion at the C-1 position of C_3F_6 is presumed by analogy with the oxyanion results described earlier, and the established reactivity of C_3F_6 nucleophiles in solution.[23] Sequential HF-loss may occur by linear (path **a**) or cyclic (path **b**) mechanisms. Nibbering and co-workers also observed that certain allylic carbanions will undergo addition/HF-elimination reactions with fluorocarbons such as C_6F_6, $C_6F_5OCH_3$ and $CF_2{=}CF_2$.[15] The use of unsymmetrically labelled carbanions demonstrated that linear and stepwise cycloaddition mechanisms compete in the reactions between $CF_2{=}CF_2$ and deprotonated methacrolein.

Benzyl anion ($C_6H_5CH_2^-$) can also produce linear and/or cyclic $[M + C_3F_6 - 2HF]^-$ products, shown as structures **4a** and **4b**.



$Ph{-}C{\equiv}C{-}\bar{C}F{-}CF_3$

<u>4a</u>



<u>4b</u>

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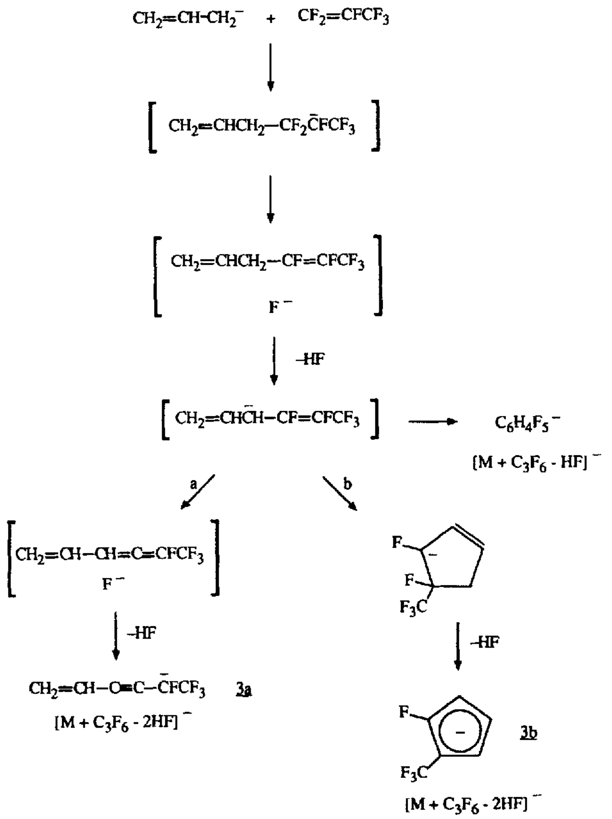
*ΔH_f ($CH_3CO_2^-$) = $-120{\cdot}8$ kcal/mol;[7b] ΔH_f (CH_3CFO) = -106 kcal/mol;[21] ΔH_f (CH_2CO) = $-11{\cdot}4$ kcal/mol;[21] ΔH_{rxn} ($B_{AC}2$) = -60 kcal/mol, ΔH_{rxn} (E2) = -30 kcal/mol.



Scheme 3

Thermochemical estimates indicate that cyclopentadienyl anion structures such as **3b** and **4b** are more stable than the linear isomers and thus represent the thermodynamically favored products.*

In order to distinguish between structures **4a** and **4b** as the product of the benzyl anion reaction, C_3F_6 was allowed to react with $C_6H_5CD_2^-$ (made by *in situ* H/D exchange between $C_6H_5CH_2^-$ and D_2O)[24] in the collision chamber of the triple quadrupole at low ion kinetic energies (<1 eV). The product ion resulting from C_3F_6 addition and loss of two DF molecules (*m/z* 201), which must correspond to structure **4a**, was six times more abundant than the adduct minus (HF + DF) (*m/z* 202) which corresponds to structure **4b**. Thus, the linear mechanism is favored for the benzyl anion. Linear condensation is also considered likely for the reaction between C_3F_6 and the cyanomethyl anion, since cyclization would require the intermediacy of a high-energy, small-ring cumulene.

Based on the observations outlined above, we assign the addition/HF-elimination reaction (henceforth referred to as '$[M + C_3F_6 - n\text{HF}]^-$') to be a characteristic indicator for reaction of

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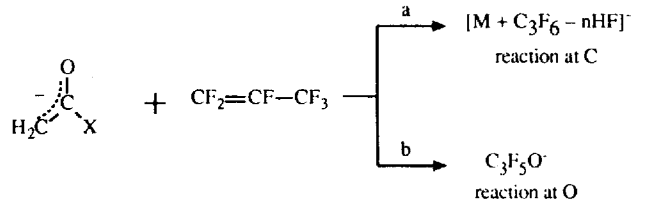
*Heats of formation for neutral fluorocarbons estimated from Benson equivalents.[20] ΔH_f (3a) = −144 kcal/mol, based on ΔH_f (parent acid) = −138 kcal/mol and an estimated acidity of 360 kcal/mol. ΔH_f (3b) = −187 kcal/mol, based on ΔH_f (parent acid) = −161 kcal/mol and an estimated acidity of 340 kcal/mol. ΔH_f (4a) = −171 kcal/mol, based on ΔH_f (parent acid) = −160 kcal/mol and an estimated acidity of 355 kcal/mol. ΔH_f (4b) = −185 kcal/mol, based on ΔH_f (parent acid) = −155 kcal/mol and an estimated acidity of 335 kcal/mol.

C_3F_6 with carbanion nucleophiles. Thus, the appearance of $[M + C_3F_6 - nHF]^-$ ions from reaction between C_3F_6 and an enolate ion shall be interpreted to mean that the initial reaction occurred at the carbon end.

REACTIONS OF ENOLATE IONS: PRODUCT STRUCTURES AND MECHANISMS

Having established the distinct product of the reactions of C_3F_6 with pure oxyanions and carbanions, we now present the results of its reactions with acyclic and cyclic enolate ions derived from aldehydes, ketones, esters, amides and related compounds. Table 2 and Table 3 summarize the ionic product yields obtained from reactions of C_3F_6 with twenty-five different enolate ions. These reactions are all generally fast, with measured rate coefficients in the range $6 \times 10^{-10}\,cm^3/s$ to $8 \times 10^{-10}\,cm^3/s$. The observed product ions for each enolate are listed according to the two general pathways illustrated by equation (5), and the derived C/O reactivity distributions are given in the final two columns.



(5)

Table 2. Reactions of acyclic enolate ions with $CF_2{=}CFCF_3$, 0·4 torr, 298 ± 2 K

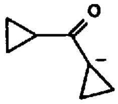
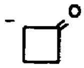
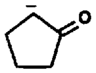
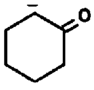
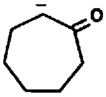
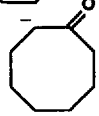
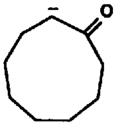
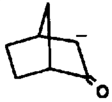
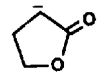
Enolate	$C_3F_5O^-(\%)$[a] *O⁻/F exchange*	$[M + C_3F_6 - nHF]^-(\%)$[b] $n = 0$	$n = 1$	$n = 2$	%C[c]	%O[c]
$HCOCH_2^-$	93	1	4	2	6(8)	94(92)
$HCOCHMe^-$	80	16	2	2	5(1)	95(99)
$HCOCMe_2^-$	11	86	3		21(0)	79(100)
$MeCOCH_2^-$	84	3	6	7	13(20)	87(80)
$EtCOCHMe^-$	67	16	8	9	20(19)	80(81)
$i\text{-}PrCOCMe_2^-$	69	22	8	1	12(4)	88(96)
$t\text{-}BuCOCH_2^-$	20	18	60	2	76(79)	24(21)
$CH_2{=}CHCOCH_2^-$	31	4	54	11	68(70)	32(30)
$c\text{-}C_3H_5COCH_2^-$	23	9	62	6	75(76)	25(24)
$Me_2NCOCH_2^-$	4		12	83	95(99)	5(1)
$MeOCOCH_2^-$	8		79	13	92(99)	8(1)
$MeOCOCHMe^-$	9		43	48	91(100)	9(0)
$PhCOCH_2^-$	2	9	88	1	98(97)	2(3)
$CF_3COCH_2^-$		3	97		100	
$FCOCH_2^-$	2		94	4	98(100)	2(0)
$MeCO\bar{C}HCOMe$	6	3	84	7	94	6

[a] Path b, equation (5), indicating initial attack at oxygen.

[b] Path a, equation (5), indicating attack at carbon.

[c] Relative percentages for attack at carbon and oxygen, neglecting adduct (see text for discussion). Values in parentheses are the C/O percentages determined for the reaction of the selected enolate with C_3F_6 in the collision chamber of the triple quadrupole at low kinetic energy.

Table 3. Reactions of cyclic enolate ions with $CF_2{=}CFCF_3$, 0·4 torr, 298 ± 2 K

Enolate	$C_3F_5O^-$(%)[a] *O^-/F exchange*	$[M + C_3F_6 - nHF]^-$(%)[b] $n = 0$	 $n = 1$	 $n = 2$	 $n = 3$	%C[c]	%O[c]
	14		76	10		86(93)	14(7)
	4	1	62	30	3	96(100)	4
	4	18	66	6	6	95(100)	5
	13	51	25	6	1,4[d]	73(64)	27(36)
	58	33	6	3		13(3)	87(97)
	75	9	7	7	2	18	82
	69	9	13	8	1	24	76
	1	11	74	10[e]	1	99(100)	1
	8		40	12	40	92(99)	8(1)

[a] Path b, equation (5), indicating initial attack at oxygen.

[b] Path a, equation (5), indicating initial attack at carbon.

[c] Relative percentages for attack at carbon and oxygen, neglecting adduct (see text). Values in parentheses are the C/O percentages determined for the reaction of the selected enolate with C_3F_6 in the collision chamber of the triple quadrupole at low kinetic energy.

[d] $n = 4$.

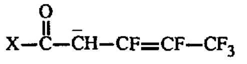
[e] An additional product corresponding to an adduct minus ($2HF + CO$) or ($HF + C_2H_4$) is observed (4%).

Before proceeding with a discussion of the trends in these data, we must first consider the structures of the product ions and the mechanisms by which they form from ambident enolate ions. Note, however, that the ultimate interpretation of the product distributions in Tables 2 and 3 does not rely upon a complete knowledge of the product ion structures. Rather, it depends solely upon the premise that the two families of products (O^-/F exchange and [M +

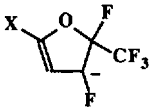
$C_3F_6 - n$HF]$^-$) arise from distinct channels that are initiated by attack at either the carbon or oxygen ends of the enolate. Clearly, were synchronous [$2\pi + 4\pi$] cycloaddition mechanisms responsible for some or all of the products, then the observed yields would have little bearing on the question of relative carbon vs. oxygen reactivities. However, since the $C_3F_5O^-$ product ion necessarily arises from a discrete oxygen attack pathway, and linear condensation mechanisms have been found for reactions with the structurally related allylic carbanions,[15] then synchronous cycloaddition mechanisms are unlikely for enolate/C_3F_6 reactions. In fact, [$2\pi + 4\pi$] cycloaddition reactions involving enolate ions are less likely than for allylic carbanions since they would initially produce a destabilized α-alkoxy carbanion cycloadduct.[25] Moreover, HF loss from this intermediate would have to proceed by a disfavored four-center, four-electron elimination mechanism.[26]

Another conceivable complication is that if addition to C_3F_6 through oxygen is ever accompanied by HF-loss, then the overall product distributions would not be indicative of the distinct carbon and oxygen alkylation pathways. However, HF-loss does not occur with any of the pure oxyanions listed in Table 1, despite the availability of relatively acidic hydrogens in certain of the F^- ion-molecule complexes that must precede $C_3F_5O^-$ formation. For example, the putative intermediate in the reaction involving acetate ion contains α-hydrogens that are sufficiently acidic for deprotonation by F^-. Nevertheless, no [M + $C_3F_6 - n$HF]$^-$ products are formed. The reaction between HO_2^- and C_3F_6 provids a more striking example. Despite the presence of an acidic hydroxyl hydrogen in the intermediate F^- ion–molecule complex ($F^- \ldots HOO{-}CF_2{=}CFCF_3$), only elimination to produce $C_3F_5O^-$ and (presumably) HOF, is observed.

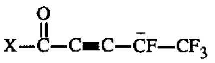
As with the allylic carbanions described earlier, both linear and cyclic structures are possible for the enolate ion C_3F_6-condensation products. Most of the acetyl derivatives, $XCOCH_2^-$, produced both single and double HF-loss products. These are likely to have the general structures **5** and **6** shown below. For enolate ions with alpha-carbon substitutents such as HCOCHMe$^-$ or EtCOCHMe$^-$, or those in which X is a hydrogen or an alkyl group such as in $HCOCH_2^-$ or $CH_3COCH_2^-$, alternative product structures involving loss of other hydrogens are conceivable (e.g. **6c** and **6d**). A pertinent observation by Nibbering and co-workers is that pentafluoroanisole reacts with both $DCOCH_2^-$ and $CD_3COCH_2^-$ in the gas phase by addition followed by loss of *both* HF and DF from the benzoannelated furan product ions.[15] Thus, hydrogens other than those on the original alpha-carbon in the enolate may become inolved in HF elimination with pentafluoroanisole. Similar possibilities exist with perfluoropropylene.


$X{-}\overset{\overset{O}{\|}}{C}{-}\bar{C}H{-}CF{=}CF{-}CF_3$

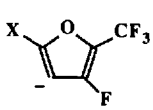
5a



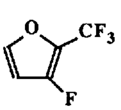
5b


$X{-}\overset{\overset{O}{\|}}{C}{-}C{\equiv}C{-}\bar{C}F{-}CF_3$

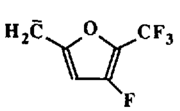
6a



6b

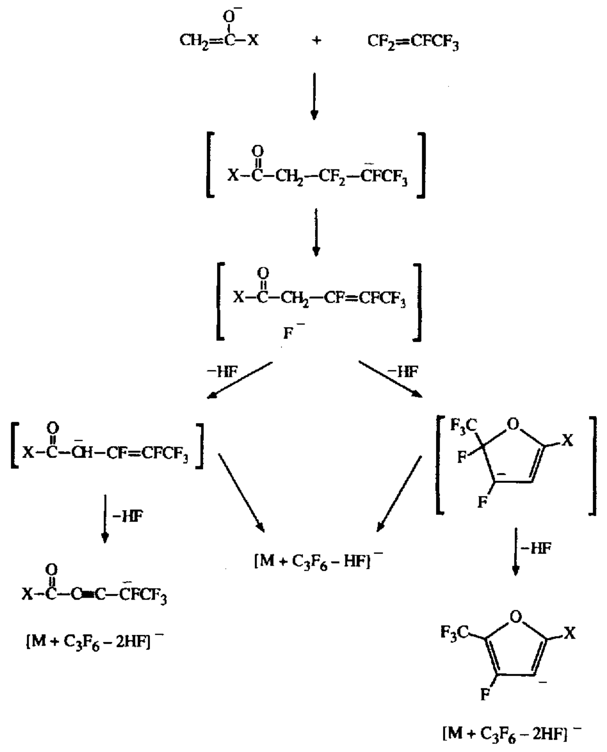


6c, X=H

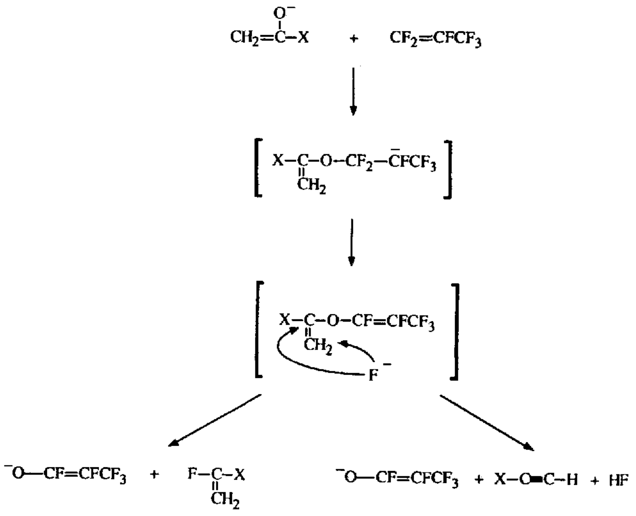


6d, X=Me

Scheme 4 outlines our view of the mechanism by which acetyl enolate ions condense with C_3F_6 through both linear and (stepwise) cycloaddition pathways, and Scheme 5 shows an

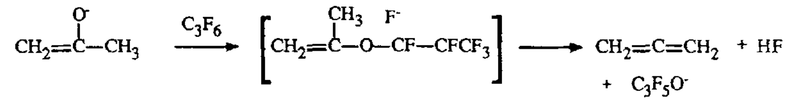


Scheme 4



Scheme 5

addition–elimination mechanism for $C_3F_5O^-$ formation. Here, we again presume that the initial addition to C_3F_6 occurs at the C_3F_6 occurs at the C-1 position (*vide supra*).[27] The key feature of these mechanisms, and the basis for the utility of C_3F_6 as a C/O reactivity probe, is the initial partitioning of the reaction between the distinct intermediates formed by addition of either the carbon or oxygen termini of the ambident reactant ion. Once this occurs, the overall product distribution is determined. Formation of an F^- ion/molecule complex rapidly follows addition in both cases. Sequential loss of HF molecules proceeds from the carbon adduct, while $C_3F_5O^-$ dissociation from the oxygen adduct takes place by an F^- induced elimination to form a neutral acetylene product. Direct *ipso* displacement of $C_3F_5O^-$ to form a vinyl fluoride does not appear to be important (*vide infra*). In cases where the X group is a hydrogen-bearing alkyl group, the final $C_3F_5O^-$ elimination step may also occur by way of an allene, equation (6).

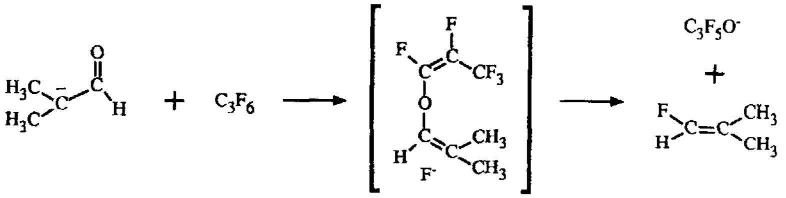


$$CH_2{=}\overset{O^-}{\overset{|}{C}}{-}CH_3 \xrightarrow{C_3F_6} \left[CH_2{=}\overset{CH_3}{\overset{|}{C}}{-}O{-}\overset{F^-}{CF}{-}CFCF_3\right] \longrightarrow CH_2{=}C{=}CH_2 + HF + C_3F_5O^- \qquad (6)$$

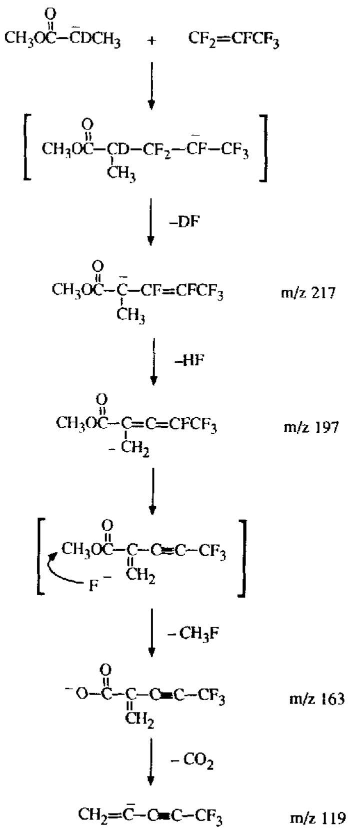
For some enolates, the number of observed HF losses exceeds the number of alpha-hydrogens, as in the case of methyl propionate enolate ($MeOCOCHMe^-$). To explicate the order and type of HF loss, the monodeuterated methyl propionate enolate was produced in the flow tube by *in situ* H/D exchange between the enolate and MeOD.[24] The deuterated enolate (*m/z* 88) was then allowed to react with C_3F_6 in Q2 at low collision energy. Product ions are observed at *m/z* 217 (1%), *m/z* 197 (80%), *m/z* 163 (18%) and *m/z* 119 (1%). We interpret the absence of a product ion corresponding to $[M + C_3F_6 - HF]^-$ (*m/z* 218) as an indication that DF-loss occurs initially, and that the remaining products arise from the resulting intermediate (*m/z* 217). Scheme 6 summarizes a plausible mechanism and product-ion structure assignment. The major product ion (*m/z* 197) is shown to extrude CH_3F. Formation of an F^-- ion/molecule complex from this intermediate cannot lead to a second HF-loss since the remaining (vinyl) hydrogens in the neutral molecule are weakly acidic. Instead, nucleophilic attack at the ester methyl group occurs to yield a carboxylate (*m/z* 163). Sufficient internal energy apparently remains in the organic ion at this point to drive the final decarboxylation reaction that yields the carbanion product[28] (*m/z* 119).

CARBON VS. OXYGEN REACTIVITY DISTRIBUTIONS

The absolute yields for the O^-/F exchange and $[M + C_3F_6 - nHF]^-$ condensation products are listed for each enolate in Table 2 and Table 3. Many of the ketone and aldehyde enolates produce adducts with C_3F_6 under the relatively high pressure conditions of our experiments. For example, isobutyraldehyde enolate produces an 80% yield of the adduct at *m/z* 233. Formation of $C_3F_5O^-$ probably proceeds by *ipso* substitution in the nascent adduct since no protons are available for elimination, equation (7). Substitution is generally slower than elimination,[29] so



(7)



Scheme 6

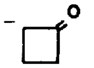
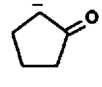
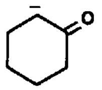
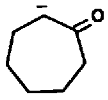
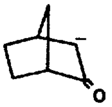
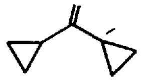
that much of the oxygen-addition intermediate is ‘trapped’ by collisional cooling rather than fragmenting to $C_3F_5O^-$. The fact that this reaction produces mainly adduct, yet occurs rapidly (k = 5·8 × 10^{-10}cm^3/s) suggests that the intermediate adduct must have a relatively long lifetime, ie that addition is essentially irreversible.

We have neglected the contribution of the adduct ion in calculating the overall C/O reactivity distributions that are shown in the last two columns in the tables. This is justified by the following observations: i) As shown in Table 4, collision-induced dissociation of the adducts in the triple quadrupole yields $C_3F_5O^-$ and HF-loss daughter ions (in addition to free enolate)* in relative yields that closely match the final C/O product ratios shown in Table 2 and Table 3. For instance, CID of the C_3F_6 adduct with isobutyraldehyde enolate yields only free enolate and $C_3F_5O^-$ as the lowest energy daughter ions under single-collision conditions. In contrast, the acetophenone enolate/C_3F_6 adduct fragments to produce only the enolate and

---

*Table 4 shows that enolates which readily produce $C_3F_5O^-$ yield less free enolate from CID of the C_3F_6 adduct than those enolates which produce mainly C-alkylation or enolates for which $C_3F_5O^-$ formation is disfavored. Acetone enolate/C_3F_6 adduct produces mainly $C_3F_5O^-$ with a small amount of free enolate and adduct −2HF. However, isobutyraldehyde enolate/C_3F_6 adduct produces mainly free enolate, presumably because the substitution process to form $C_3F_5O^-$ is kinetically disfavored with respect to direct cleavage. For the C-alkylated adducts, fragmentation by HF-loss also appears to be relatively inefficient compared to direct cleavage.

Table 4. Fragment ion yields resulting from collision-induced dissociation of enolate ion/C_3F_6 adducts[a]

Enolate	*Enolate(%)*	$C_3F_5O^-$%	$[M + C_3F_6 - nHF]^-$ (%) *n* = 1	*n* = 2	*n* = 3	*n* = 4	%*C*	%*O*
$MeCOCH_2^-$	5	92		3			3	97
$HCOCHMe^-$	10	88		2			2	98
$HCOCMe_2^-$	68	32						100
$i\text{-}PrCOCMe_2^-$	28	65	7				12	88
$t\text{-}BuCOCH_2^-$	39	10	40	11			84	16
$CH_2{=}CHCOCH_2^-$	46	15	12	27			72	28
$c\text{-}C_3H_5COCH_2^-$	16	30	38	16			64	36
$PhCOCH_2^-$	39		58	3			100	
	48		23	30			100	
	43		42	6	9		100	
	53	7	12	15	6	7	85	15
	7	92		1			1	99
	53		35	11		1	100	
	25		47	28			100	

[a] All experiments performed under single collision conditions with Ar collision gas and a 1–2 eV center-of-mass collision energy.

HF-loss products. Thus, the observed adducts most likely exist as mixtures of structures that reflect the final O^-/F exchange and $[M + C_3F_6 - nHF]^-$ product ratios produced in the bimolecular reactions. ii) Reactions of selected enolate ions with C_3F_6 in the collision chamber of the triple quadrupole at low ion kinetic energies (< 1 eV) yield $C_3F_5O^-$ and $[M + C_3F_6{-}nHF]^-$ $n \geqslant 1$ product ions which also closely match the relative C/O reactivity ratios from the flow tube experiments. These data are shown in parentheses in the last two columns of Tables 2 and 3. This is significant because C_3F_6-adducts *are not produced* at all under the relatively low pressure conditions ($P \simeq 10^{-4}$ torr) and with the shorter reaction times (*ca.* 10^{-6} s) in Q2. For example, 3-pentanone enolate produces 19% condensation products and 81% $C_3F_5O^-$ from reaction with C_3F_6 in Q2, and isobutyraldehyde enolate yields 100% $C_3F_5O^-$. These observations validate the practice of neglecting the adduct ions in computing the overall C/O reactivity distributions since the same results are obtained when the C_3F_6 reactions are carried out under conditions where stabilized adducts are completely absent.

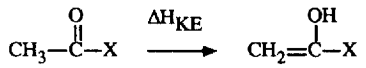
The relative C/O reactivity distributions for enolate ions listed in Table 2 and Table 3 span the full range of values from 95% reaction at oxygen to 100% reaction at carbon. In general, it can be seen that most of the acyclic ketone and aldehyde enolates react mainly (or exclusively) at oxygen, while all of the acetyl enolates ($XCOCH_2^-$) bearing electron-withdrawing or π-donating central substituents yield predominantly carbon condensation products. Furthermore, a general decrease in the amount of oxygen reactivity is observed in the small-ring enolates relative to the larger-ring enolates.

These results parallel the trends observed in condensed-phase studies of regioselectivity in enolate ion alkylations. For example, it is well-known that ketone and aldehyde enolates are subject to oxygen-alkylation or silylation under conditions which yield only carbon-alkylation or silylation of ester enolates.[30] Also, a greater preference for carbon alkylation of cyclopentanone enolate relative to cyclohexanone enolate has been observed in dipolar, aprotic solvents.[31]

The present results also bear a close similarity to the results described previously for enolate ion reactions with 6,6-dimethylfulvene (DMFU).[32] That is, a wide range of reactivity is exhibited by the enolates that appears to be a sensitive function of the nature of the central substitutent as well as the enolate geometry (as opposed to size). Just as in the DMFU reactions, the behavior of the amide enolates, ester enolates and small-ring enolates is quite different from that of aldehyde enolates, ketone enolates and larger-ring enolates.

It is important to note that both the carbon and oxygen condensation channels in equation (7) are strongly exothermic. For example, using Benson group-equivalents[20] and reasonable estimates of gas phase acidities, we calculate that addition followed by HF-loss to form structures like **5** or **6** is more than 40 kcal/mol exothermic for most of the ions listed in Table 2 (see footnote on page 396). Furthermore, formation of $C_3F_5O^-$ from enolate/C_3F_6 reactions as shown in Scheme 5 is generally exothermic by 30–45 kcal/mol, depending upon which neutral products are formed. Therefore, we are dealing here with highly variable, kinetically controlled product distributions that arise from a competition between two strongly exothermic reaction channels. The rapid rates found for these reactions are consistent with this view.

Most of the variation in the C/O reactivity ratios can be understood in terms of expected trends in the keto–enol energy differences for the parent carbonyl compounds, ΔH_{KE}, equation (8).



$$CH_3-\overset{\overset{O}{\|}}{C}-X \xrightarrow{\Delta H_{KE}} CH_2=\overset{\overset{OH}{|}}{C}-X \qquad (8)$$

Experimentally determined values of ΔH_{KE} are available for acetaldehyde (9·8 kcal/mol) and acetone (13·9 kcal/mol),[33] and from the recently evaluated thermochemical group equivalent for an enolic oxygen,[33] values for other carbonyl compounds can be estimated. In order to facilitate discussion of the C_3F_6 results, we have summarized, measured and estimated keto–enol energy differences in Table 5. An insightful discussion of substituent effects on ΔH_{KE} has been published recently by Heinrich and co-workers.[34] In general, almost all aldehydes and simple acyclic ketones have ΔH_{KE} values from 10–15 kcal/mol, while acetyl compounds bearing π-donating substituents on the carbonyl carbon have ΔH_{KE} values nearly three times larger (30–35 kcal/mol). Alpha-branching reduces ΔH_{KE} somewhat by specific stabilization of the enol tautomer. A smooth increase in ΔH_{KE} with decreasing ring size is evident for the cyclic ketones which arises from strain-effects in the smaller-ring enols.[35]

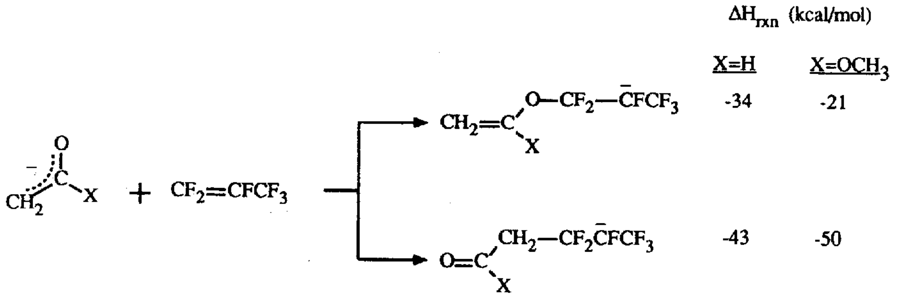
Table 5. Calculated and experimental keto–enol energy differences

compound	ΔH_{KE} (kcal/mol)[a]
CH_3CHO	9·8[b]
CH_3COCH_3	13·9[b]
CH_3COt-Bu	12·3
$CH_3CO(c$-$C_3H_5)$	13·6
CH_3CONMe_2	35·2
CH_3COOCH_3	29·4
$CH_3CH_2COOCH_3$	26·5
CH_3COCF_3	5·0
CH_3COF	28·0
dicyclopropyl ketone	23·1
cyclobutanone	18·7
cyclopentanone	12·0
cyclohexanone	10·2
cycloheptanone	14·6
cyclooctanone	16·0
cyclononanone	16·7
2-norbornanone	19·2
α–butyrolactone	28·0

[a] Estimated from thermochemical group-equivalents, references 20, 33.

[b] Experimental values, reference 33.

Comparison of the data in Tables 2–5 shows that, with few exceptions (*vide infra*), enolates derived from compounds with low values of ΔH_{KE} (10–15 kcal/mol) react mainly (80–95%) through oxygen, while those derived from compounds with high ΔH_{KE} values (>20 kcal/mol) exhibit a strong preference (85–100%) for carbon condensation. It should also be noted that weakly basic enolates such as $CF_3COCH_2^-$ (PA =350 kcal/mol[7b]) show only carbon alkylation regardless of keto–enol energy difference of the parent acid. A general correlation of this type is not surprising and implies that, even though the *overall* C_3F_6 condensation reactions are substantially exothermic, the kinetically controlled product ratios are largely determined by the energetics of the initial step involving addition of C_3F_6 to either the oxygen or carbon end of the enolate, equation (9). These energies, in turn, must be



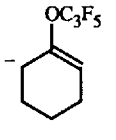
(9)

correlated with the relative thermodynamic basicities at the carbon and oxygen termini, viz., the C_3F_6 and proton binding energies to an enolate are evidently proportional. While there are insufficient thermochemical data available to confirm this hypothesis completely, it is a reasonable conclusion in view of the many well-established correlations between proton binding energies and other Lewis acid binding energies of negative ions and neutral compounds.[36]

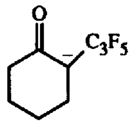
Estimates for the heats of formation of the tautomeric ions shown in equation (9) show that C_3F_6-addition through carbon is strongly exothermic for ketone ($X = CH_3$), aldehyde ($X = H$) and ester ($X = OCH_3$) enolates (*ca.* 45–50 kcal/mol). However, C_3F_6-addition through oxygen is considerably more exothermic for the ketone enolates (*ca.* 35 kcal/mol) than for the ester enolates (*ca.* 20 kcal/mol). Thus, the partitioning between the two reactive channels in the course of an enolate ion/C_3F_6 collision cannot be the result of one or the other adduct being energetically inaccessible. Rather, it is likely that the partitioning arises from the presence of kinetic barriers impeding addition of C_3F_6 to either of the two ends of the enolate, and that the relative magnitudes of these barriers are directly proportional to the overall addition energies.

The ΔH_{KE} values serve as good general predictors of C vs. O regioselectivity in reaction of most acyclic enolates with C_3F_6. However, the results for t-$BuCOCH_2^-$, $CH_2{=}CHCOCH_2^-$, c-$C_3H_5COCH_2^-$ and $PhCOCH_2^-$ are aberrant. That is, based on their ΔH_{KE} values, one might predict that these ions would behave like other ketone enolates and show >80% reaction at oxygen. However, carbon alkylation dominates by a factor of 2–3 for the first three, and is almost the exclusive reaction for $PhCOCH_2^-$. We also note that while the overall trend for the cyclic enolates is reasonable, the dominance of carbon alkylation in cyclopentanone and cyclohexanone enolate ions is unexpected.[3]

One possible explanation is that for these systems the initial C_3F_6 addition through oxygen is followed by HF-loss. This would result in an erroneously skewed C/O product distribution as determined by our criteria. We can test this experimentally by examining the structures of the $[M + C_3F_6 - HF]^-$ product ions observed with the anomalous enolates, since quite different structures would be expected depending upon whether HF-loss is preceded by oxygen or carbon addition. For the cyclohexanone enolate system, we consider the two structures shown below to be likely alternatives for the observed $[M + C_3F_6 - HF]^-$ ion (**7**). CID does not allow a distinction to be made, as only additional HF-loss is observed. Ion **7** does not exhibit any H/D exchange with D_2O or MeOD,[22] and it is unreactive with both N_2O[37] and n-BuONO.[38] While these are negative results, they are more consistent with C-alkylated form **7b** since an allylic carbanion such as **7a** would be expected to show reactivity with each of these reagents. Similar results are obtained with $[M + C_3F_6 - HF]^-$ ions derived from the other anomalous enolates. We therefore conlude that the C/O product ratios shown in Table 2 for these systems correctly reflect the final amounts of carbon vs. oxygen condensation and not a mixing of the oxygen addition and HF-loss pathways.



7a



7b

The question still remains as to the origin of the unexpectedly low oxygen-alkylation percentages in these systems. For the cyclic enolates the answer may be in specific hindrance of the $C_3F_5O^-$-formation channel due to ring-strain effects. That is, F^--induced elimination of $C_3F_5O^-$ from a cyclic enol ether (Scheme 5) would necessarily produce a cyclic alkyne or allene. For medium-ring (C_5, C_6) systems these are prohibitively high in energy[39,40] and, as a result, $C_3F_5O^-$ formation must proceed through a slower *ipso* substitution mechanism. For the C_7–C_9 ring system the cyclic alkynes and allenes are energetically accessible;[39,40] $C_3F_5O^-$ elimination can proceed normally. The abnormally high percentage of C_3F_6-adduct formed by cyclohexanone enolate is consistent with this hypothesis (cf. isobutyraldehyde enolate). Thus, the abrupt change in the C/O alkylation ratio between cyclohexanone enolate and cycloheptanone enolate appears not to reflect the intrinsic nucleophilicities of the carbon and oxygen termini, but rather the relative availability of the $C_3F_5O^-$ formation routes. Such an interpretation suggests that our C_3F_6 probe is biased towards carbon-alkylation when it is applied to cyclic enolates, and offers an explanation for the disparity between our results for cyclohexanone enolate (73% C, 27% O) and Ellison's neutral collection experiment (100% O).

We see no obvious obstacles to $C_3F_5O^-$ formation in the acyclic enolates *t*-$BuCOCH_2^-$, $CH_2{=}CHCOCH_2^-$, *c*-$C_3H_5COCH_2$ and $PhCOCH_2^-$. Alpha-hydrogens are available for eliminating $C_3F_5O^-$ via the acetylene pathway (Scheme 5). While it is true that the α' hydrogens in $CH_2{=}CHCOCH_2^-$ and *c*-$C_3H_5COCH_2^-$ have reduced kinetic acidities, and they are absent altogether in *t*-$BuCOCH_2$ and $PhCOCH_2^-$, this is not likely to be a factor since aldehyde enolates also lack α' hydrogens, yet $C_3F_5O^-$ formation is facile. It is possible that the keto–enol energy differences for the parent acids of these enolates are actually much larger than the estimated values shown in Table 5. If this were so then a greater amount of carbon alkylation would result. The group equivalent method used here[20,33] may not adequately account for π-conjugation and/or steric effects in either tautomer. For this reason, experimental measurements or reliable calculations of the gas-phase keto–enol energy differences for these particular systems are of interest.

CONCLUSION

Perfluoropropylene is a versatile neutral reagent for gas-phase negative ion studies that yields characteristic ionic products in its reactions with oxyanions and carbanions. The ambident enolate ions show a wide range or reactivity with C_3F_6, from near complete oxygen alkylation to exclusive carbon alkylation. The preference for reaction with C_3F_6 at the carbon or oxygen end of an enolate is strongly influenced by the nature of the central substituent, i.e. most aldehyde and ketone enolates react mainly through oxygen, while ester enolates, amide enolates and enolates bearing electronegative central substituents react preferentially through carbon. Ring-size in cyclic ketone enolates also exerts a significant effect. Small ring enolates react through carbon and larger ring enolates react through oxygen. The keto–enol energy difference for the parent carbonyl compound appears to be a good predictor of C vs. O regioselectivity, although some notable exceptions are evident. Compounds with low ΔH_{KE} values (10–15 kcal/mol) tend to react through oxygen, while higher values of ΔH_{KE} (30–40 kcal/mol) are associated with reaction through carbon. The apparent general preference for carbon alkylation by the medium ring (C_5, C_6) enolates appears to be an artifact of the C_3F_6 probe reaction that arises from ring strain effects in the reactive intermediates.

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REFERENCES

1. a) N. Kornblum, P. J. Berrigan and W. J. LeNoble, *J. Am. Chem. Soc.*, **85**, 1141 (1963).
   b) R. Gompper, *Angew. Chem. Int. Ed.*, **3**, 560 (1964).
   c) W. J. LeNoble, *Synthesis*, **1**, 1 (1970).
   d) H. O. House, *Modern Synthetic Reactions*, 2nd ed.; The Benjamin/Cummings Publishing Co.; Menlo Park CA, 1972; pp. 492–570.
   e) L. M. Jackman and B. C. Lange, *Tetrahedron*, **33**, 2737 (1977).
   f) O. A. Reutov and A. L. Kurtz, *Russ. Chem. Rev.*, **46**, 1040 (1977).
2. R. Gompper and H. U. Wagner, *Angew. Chem. Int. Ed.*, **15**, 321 (1976).
3. M. E. Jones, S. R. Kass, J. Filley, R. M. Barkley and G. B. Ellison, *J. Am. Chem. Soc.*, **107**, 109 (1985).
4. K. N. Houk and M. N. Paddon-Row, *J. Am. Chem. Soc.*, **108**, 2659 (1986).
5. J. E. Bartmess, R. L. Hays and G. Caldwell, *J. Am. Chem. Soc.*, **108**, 1338 (1981).
6. K. R. Lane, R. E. Lee, L. Sallans and R. R. Squires, *J. Am. Chem. Soc.*, **106**, 5767 (1984).
7. a) J. E. Bartmess and R. T. McIver, in *Gas Phase Ion Chemistry*, M. T. Bowers, Ed.; Academic Press, 1979. Vol. 2.
   b) S. G. Lias, J. E. Bartmess, J. F. Leibman, J. L. Holmes, R. D. Levin and W. G. Mallard, *J. Phys. Chem. Ref. Data Suppl., 1988,* **17**, Suppl. 1.
8. C. H. DePuy, V. M. Bierbaum, R. J. Schmitt and R. H. Shapiro, *J. Am. Chem. Soc.*, **100**, 2920 (1978).
9. R. R. Squires and C. H. DePuy, *Org. Mass Spec.*, **17**, 187 (1982).
10. D. Smith and N. G. Adams, *J. Phys. B.*, **9**, 1439 (1976).
11. T. Su, A. C. L. Su, A. A. Viggiano and J. F. Paulson, *J. Phys. Chem.*, **91**, 3683 (1987).
12. a) D. Smith and N. G. Adams, in *Gas Phase Ion Chemistry*, M. T. Bowers, Ed.; Academic Press, New York, 1979, Vol. 1.
    b) S. T. Graul and R. R. Squires, *Mass Spectrom. Rev.*, **7**, 263 (1988).
13. P. H. Dawson, J. B. French, J. A. Buckley, D. J. Douglas and D. Simmons, *Org. Mass Spec.*, **17**, 205 (1982).
14. a) J. P. Schmidt, P. H. Dawson and N. Beaulieu, *Org. Mass Spec.* **20**, 269 (1985).
    b) M. T. Kinter and M. M. Bursey, *J. Am. Chem. Soc.*, **108**, 1797 (1986).
15. a) S. Ingemann, N. M. M. Nibbering, S. A. Sullivan and C. H. DePuy, *J. Am. Chem. Soc.*, **104**, 6520 (1982).
    b) S. Ingemann and N. M. M. Nibbering, *Nouv J. Chim.*, **8**, 299 (1984).
    c) J. C. Kleingeld and N. M. M. Nibbering, *Recl. Trav. Chim. Pays. Bas*, **103**, 87 (1984).
16. a) S. M. J. Briscase and J. M. Riveros, *J. Am. Chem. Soc.*, **97**, 230 (1975).
    b) J. M. Riveros and K. Takashima, *Can. J. Chem.*, **54**, 1839 (1976).
17. S. A. Sullivan and J. L. Beauchamp, *J. Am. Chem. Soc.*, **99**, 5017 (1977).
18. For reviews see:
    a) R. D. Chambers and R. H. Mobbs, *Adv. Fluor. Chem.*, **4**, 50 (1965).
    b) I. L. Knunyants and U. R. Polischuk, *Russ. Chem. Rev.*, **45**, 574 (1976).
    c) N. P. Gambaryan and E. M. Rokhlin, *Russ. Chem. Rev.*, **55**, 480 (1986).
    d) R. E. Banks and J. C. Tatlow, *J. Fluor. Chem.*, **33**, 227 (1986).
19. D. H. Dixon, T. Fukunaga and B. E. Smart, *J. Am. Chem. Soc.*, **108**, 4027 (1986).
20. S. W. Benson, *Thermochemical Kinetics,* 2nd ed.; Wiley-Interscience: New York, 1976.
21. J. B. Pedley and J. Rylance, *Sussex-NPL Computer Analyzed Thermochemical Data,* U. Sussex, 1977.
22. a) K. Takashima and J. M. Riveros, *J. Am. Chem. Soc.*, **100**, 6128 (1978).
    b) J. C. Kleingeld, N. M. M. Nibbering, J. J. Grabowski, C. H. DePuy, E. K. Fukuda and R. T. McIver, *Tet. Lett.*, **23**, 4755 (1982).
23. a) S. Dixon, *J. Org. Chem.*, **21**, 400 (1956).
    b) W. Dmowski, *J. Fluor. Chem.*, **18**, 25 (1981).
    c) M. Makosza and H. Plenkiewicz, *J. Fluor. Chem.*, **24**, 387 (1984).
24. a) J. H. Stewart, R. H. Shapiro, C. H. DePuy and V. M. Bierbaum, *J. Am. Chem. Soc.*, **99**, 7650 (1977).
    b) C. H. DePuy, V. M. Bierbaum, G. K. King and R. H. Shapiro, *J. Am. Chem. Soc.*, **100**, 2921 (1978).

25. a) T. Clark, H. Korner and P. v. R. Schleyer, *Tet. Lett.*, **21**, 743 (1980).
    b) G. W. Spitznagel, T. Clark, J. Chandrasekhar and P. v. R. Schleyer, *J. Comp. Chem.*, **3**, 363 (1982).
26. C. R. Moylan and J. I. Brauman, *J. Am. Chem. Soc.*, **107**, 761 (1985).
27. H. Plenkiewicz, *J. Fluor. Chem.*, **36**, 319 (1987).
28. R. N. McDonald and A. K. Chowdhury, *J. Am. Chem. Soc.*, **104**, 901 (1982).
29. a) C. H. DePuy and V. M. Bierbaum, *J. Am. Chem. Soc.*,**103**, 5034 (1981).
    b) L. J. de Koning and N. M. M. Nibbering, *J. Am. Chem. Soc.*, **109**, 1715 (1987).
30. a) O. A. Reutov, I. P. Beletskaya and A. L. Kurts, *Ambient Anions,* J. P. Michael, Ed. Consultants Bureau, New York, 1983, p. 100 and references therein.
    b) P. F. Hudrlik, D. Peterson and D. Chou, *Syn. Comm.*, **5**, 359 (1975).
31. G. J. Heisewolf and H. Kloosterziel, *Rec. Trav. Chim. Pays-Bas.*, **89**, 1153 (1970).
32. M. D. Brickhouse and R. R. Squires, *J. Am. Chem. Soc.*, **110**, 2706 (1988).
33. J. L. Holmes and F. P. Lossing, *J. Am. Chem. Soc.*, **104**, 2468 (1982).
34. N. Heinrich, W. Koch, G. Frenking and H. Schwarz, *J. Am. Chem. Soc.*, **108**, 593 (1986).
35. K. B. Wiberg, D. J. Wasserman, E. J. Martin and M. A. Murcko, *J. Am. Chem. Soc.*, **107**, 6019 (1985).
36. S. F. Smith, F. Chandrasekhar and W. L. Jorgensen, *J. Phys. Chem.*, **86**, 3308 (1982) and references therein.
37. S. Kass. J. Filley, J. M. Van Doren and V. H. DePuy, *J. Am. Chem. Soc.*, **108**, 2849 (1986).
38. G. K. King, M. M. Maricq, V. M. Bierbaum and C. H. DePuy, *J. Am. Chem. Soc.*, **103**, 7133 (1981).
39. S. Olivella, M. A. Pericas, A. Ricra and A. Sole, *J. Org. Chem.*, **52**, 4160 (1987).
40. R. O. Angus, M. W. Schemidt and R. P. Johnson, *J. Am. Chem. Soc.*, **107**, 532 (1985).