

## Taming halonium metathesis

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Dedicated to Jack Beauchamp on the occasion of his 60th birthday.

### Abstract

The halonium metathesis reaction of ketones and aldehydes,  $>C=O + XF^+ \rightarrow >C=F^+ + X=O$  is difficult to harness for three reasons: (1) the interchange of  $F^+$  for  $O$  is so exothermic that the  $>C=F^+$  product ion often decomposes further; (2) the adduct of  $XF^+$  to the carbonyl oxygen frequently undergoes side reactions to the virtual exclusion of metathesis; and (3) the metathesis ion is liable to rearrange to a mixture of isomers. Several approaches have been explored to make this reaction a useful source of gaseous fluoroalkyl cations. DFT calculations reinforce the intuition that cyclopentenone should give a good yield of metathesis ions in its ion–molecule reaction with  $CF_3^+$ , an expectation that is borne out by experiment. Other approaches have met with less dramatic success. Variation of  $XF^+$  gives a number of interesting results, but little improvement over  $CF_3^+$ . Deuterium substitution at the carbon adjacent to the carbonyl ( $\alpha$ -position) does not restrain further decomposition, but deuteration of the next carbon ( $\beta$ -position) does appear to do so. The isotopic labeling experiments indicate that the prevalent mode of decomposition requires hydrogen shift followed by a 1,3-elimination of HF. Observed side reactions of adduct ions include alkene expulsion to yield  $CF_3$ -containing products (such as  $m/z$  125 from the reaction of cycloalkanones with  $CF_3^+$ ) and direct elimination of HF (as conjectured for the reaction of  $CFO^+$  with diethyl ketone, with concurrent loss of  $CO_2$ ). Structures of ion–molecule reaction products can be reliably inferred only when the expected mechanism yields the minimum energy structure for that molecular formula. (Int J Mass Spectrom 222 (2003) 451–463)  
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### 1. Introduction

Because fluorine is the most electronegative element, the properties of fluorinated ions have intrigued ion chemists for decades. Thirty years ago, Beauchamp and coworkers initiated a series of investigations that demonstrated the stability of carbocations having a single fluorine attached directly

to the  $sp^2$  center [1,2]. Not long afterwards, Ridge measured the proton affinities of fluoroethylenes [3] and showed that a single fluorine stabilizes a positive charge, but that additional fluorines tend to destabilize it. At about the same time, Eyler and coworkers [4,5] discovered a bimolecular gas phase reaction that exchanges  $F^+$  for  $O$  (Eq. (1)), which transforms ketones into fluoroalkyl cations.

Eq. (1) depicts two resonance structures for the fluoroalkyl cation, one in which the positive charge is

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with other fluorinated ions besides  $\text{CF}_3^+$ , in order to gain better understanding why those ketones give poor yields of metathesis ions.

## 2. Experimental

Ion–molecule reactions were studied in a Bruker CMS 47-X FT-ICR spectrometer equipped with an external ion source at the Ecole Polytechnique.  $\text{CF}_3^+$  ( $m/z$  69) was made by electron ionization of  $\text{CF}_4$  or else produced, along with  $\text{C}_3\text{F}_7^+$  ( $m/z$  169), by EI on 2-iodoperfluoropropane (Aldrich Chemical Co.). Reagent ions were formed in the external ion source and transferred to the ICR cell, where they were trapped and isolated. In the same fashion,  $\text{CFO}^+$  ions ( $m/z$  47) were produced by electron ionization of oxalyl fluoride (Oakwood Products, Inc.) in the external ion source and transferred to the ICR cell. Desired reactant ions were isolated in the cell by a series of rf ejection pulses to remove all other ions. Except where otherwise indicated, these ions, once isolated, were allowed to relax by collisions with argon bath gas at  $(2\text{--}3) \times 10^{-7}$  mbar and then permitted to react with neutrals (on the order of  $10^{-8}$  mbar static pressure) in the presence of argon.

$\text{CF}_4$  chemical ionization (CI) spectra were recorded using  $\approx 10^{-4}$  mbar of  $\text{CF}_4$  reagent gas in the EI/CI ion source of either a ZAB 2F two-sector (B–E) mass spectrometer (with direct injection of liquid samples) or an HP5989A quadrupole mass spectrometer, with sample introduction by means of a GC via a  $15\text{ m} \times 0.25\text{ mm}$  DB-WAX capillary column in series with a  $30\text{ m} \times 0.25\text{ mm}$  DB-5HT column mounted in an HP5890 gas chromatograph. Peak intensity ratios are reported for source mass spectra, unless otherwise indicated. CAD experiments were performed on the two-sector instrument with an 8 kV beam selected from the first sector that was allowed to collide with helium gas in the second field-free region.

Unlabeled carbonyl compounds used for this study were obtained commercially. Monodeuterated diisopropyl ketone,  $(\text{CH}_3)_2\text{CDCOCH}(\text{CH}_3)_2$ , was synthesized by reaction of  $(\text{CH}_3)_2\text{CDCOCl}$  (pre-

pared by repetitive exchange of isobutyric acid with acidic  $\text{D}_2\text{O}$ , followed by conversion to the acid chloride using  $\text{SOCl}_2$ ) with isopropylmagnesium chloride.  $\text{CD}_3$ -containing compounds were obtained by base-promoted alkylation of appropriate ketones with  $\text{CD}_3\text{I}$ , as described elsewhere [10]. Other deuterated compounds were prepared by base-catalyzed repetitive exchange with  $\text{D}_2\text{O}$ .

Density functional calculations (at B3LYP/6-311G\*\* unless otherwise specified) were performed using GAUSSIAN 98. Basis set superposition error for dissociation thermochemistry was estimated using counterpoise, with energies for individual fragments calculated both with and without ghost orbitals using the “Massage” option. Harmonic vibrational frequencies were computed for all optimized geometries and used without scaling to calculate zero point energy corrections. Isotopic shifts of vibrational frequencies were computed using harmonic force constant matrices.

## 3. Results

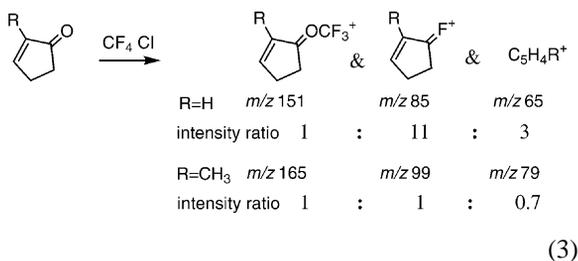
These experiments sought to find an efficient way to make monofluoroalkyl ions with more than three carbon atoms via halonium metathesis, where one might assign the structure of the fluorinated ion. Two approaches were investigated, variation of the carbonyl substrate and variation of the  $\text{F}^+$  donor. The first approach gives promising results for two unsaturated ketones and an intriguing outcome for a deuterated, saturated ketone. The second approach has not, to date, succeeded, although it reveals new aspects of the decompositions of the excited fluoroalkyl cations. Results of both approaches are described.

In searching for a carbonyl compound that could be converted to a stable fluoroalkyl cation via halonium metathesis, it appeared necessary to meet three criteria: (1) that expulsion of neutral hydrocarbon from the adduct ion not compete with halonium metathesis; (2) that the desired ion correspond to a global minimum on its potential energy surface; and (3) that subsequent elimination of HF be unfavorable. Since (as noted

above for unsaturated aldehydes and discussed below for saturated ketones) HF elimination often takes place via rearrangement of metathesis ions, an unsaturated ketone seemed like a plausible choice.

### 3.1. Cyclopentenone and 2-methylcyclopentenone

In order to make HF elimination thermodynamically unfavorable, we hit upon the idea of looking at cyclopentenones, for which elimination of HF would lead either to ring opening or to a cyclopentadienyl cation. Recent discussion of cyclopentadienyl cations leaves open the question of whether they can be formed [12], but simple Hückel theory predicts them to be antiaromatic and, therefore, thermochemically unfavorable [13].



CF<sub>4</sub> CI gives a copious yield of metathesis ions from both cyclopentenone and 2-methylcyclopentenone. Eq. (3) summarizes the most abundant products formed in the ZAB ion source. Ion–molecule reaction rates were measured for cyclopentenone in the ICR (without any argon relaxing gas) at a pressure of  $4.5 \times 10^{-9}$  Torr (based on the ion gauge calibration equation of Bartmess and Georgiadis [14] and a polarizability of cyclopentenone  $\alpha = 9 \text{ \AA}^3$ ). The disappearance of CF<sub>3</sub><sup>+</sup> corresponds to a second-order rate constant  $k = 1.8 \times 10^{-9} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ . The observed products are the same as observed in the ZAB ion source: the halonium metathesis ion ( $m/z$  85) and the ion corresponding to loss of HF from the metathesis ion ( $m/z$  65). The  $m/z$  85 ion, in turn, reacts with the parent neutral via proton transfer to give protonated parent ion ( $m/z$  83) with a second-order rate constant  $k = 1.5 \times 10^{-9} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ . The  $m/z$  65 ion reacts with the parent neutral much more slowly, giving C<sub>7</sub>H<sub>7</sub><sup>+</sup>

( $m/z$  91), presumably with concomitant formation of ethylene and CO. Extrapolating the relative  $m/z$  85 and 65 product abundances to zero time gives a branching ratio of approximately 5, as compared with a value of 3.7 seen in the ion source of the ZAB. By contrast, CFO<sup>+</sup> reacts with cyclopentenone to yield exclusively  $m/z$  65. This may represent the first preparation of the parent cyclopentadienylium cation in its singlet state.

In both the ZAB ion source and the ICR, ions from halonium metathesis are much more intense than those from subsequent HF loss. Product ions are observed in the ZAB source that are not detected in the ICR: namely, ions from simple attachment of CF<sub>3</sub><sup>+</sup> to cyclopentenone, which occur to an extent not previously seen for any other carbonyl compound. For 2-methylcyclopentenone, the attachment ion is the most intense peak from CF<sub>4</sub> CI. In order to probe ion structures in greater detail, CAD and MIKE studies were performed. The CF<sub>3</sub><sup>+</sup> adduct ion from 2-methylcyclopentenone decomposes exclusively via expulsion of CF<sub>2</sub>O (the metathesis reaction), which leaves little doubt as to its structure. This confirms that criterion (1) above has been met.

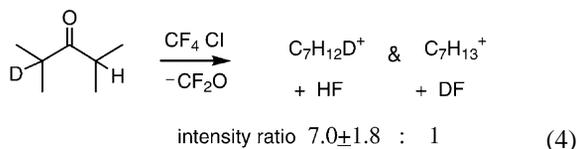
HF loss dominates the CAD spectrum of the metathesis ion ( $m/z$  99) from 2-methylcyclopentenone. That peak is composite, a superposition of a large Gaussian component upon a much smaller flat top peak. Loss of H<sub>2</sub> is observed at about one-seventh the intensity of the Gaussian component of HF loss, with a smaller peak from HF + H<sub>2</sub> loss and a much smaller peak from H loss. Finally, the CAD of  $m/z$  79 from 2-methylcyclopentenone exhibits only H<sub>2</sub> loss.

The metastable ion decomposition of the metathesis ion from cyclopentenone ( $m/z$  85) displays a flat top peak for HF loss in its MIKE spectrum with a barely detectable Gaussian (or nearly so) feature superimposed upon it. In its CAD spectrum,  $m/z$  85 exhibits intense losses of H and H<sub>2</sub> (Gaussian peaks, with about a 2:3 ratio of peak heights), with a less intense loss of HF. The CAD fragment from HF loss has a composite peak shape, a Gaussian peak (or nearly so, roughly one-eighth the height of the H<sub>2</sub> loss peak) superimposed upon a flat top peak of comparable intensity. The composite nature of the HF losses from  $m/z$

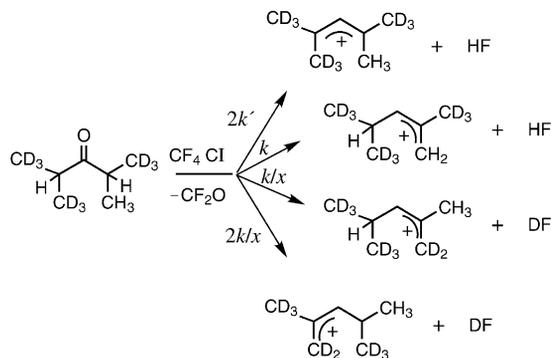
85 and 99 suggests that a ring-opening pathway may compete with formation of cyclopentadienyl cations.

### 3.2. Diisopropyl ketone and diethyl ketone (3-pentanone)

The principal reaction of diisopropyl ketone with  $\text{CF}_3^+$  produces  $\text{CH}_3\text{CH}=\text{OCF}_3^+$  ( $m/z$  113) via elimination of  $\text{C}_5\text{H}_{10}$  from the  $\text{CF}_3^+$  adduct. Chemical ionization of diisopropyl ketone with  $\text{CF}_4$  reagent gas yields  $m/z$  55 as the next most abundant ion (about three-quarters the intensity of  $m/z$  113). A much smaller amount of  $(\text{CH}_3)_2\text{C}=\text{OCF}_3^+$  is produced via  $\text{C}_4\text{H}_8$  loss from the  $\text{CF}_3^+$  adduct [10]. The abundance of the ion whose mass corresponds to metathesis ( $m/z$  117) is on the order of 0.01 that of  $\text{CH}_3\text{CH}=\text{OCF}_3^+$ . We surmise that  $m/z$  55 arises via loss of propene + HF +  $\text{CF}_2\text{O}$  from the  $\text{CF}_3^+$  adduct, and it is about 20 times more abundant than the ion ( $m/z$  97) produced simply by loss of HF from the metathesis ion.  $\text{CF}_4$  CI of the dideuterated ketone  $[(\text{CH}_3)_2\text{CD}]_2\text{C}=\text{O}$  gives  $m/z$  114 ( $\text{CH}_3\text{CD}=\text{OCF}_3^+$ ) and  $m/z$  56 as the most abundant ions, indicating that both ion–molecule reaction products retain one deuterium.

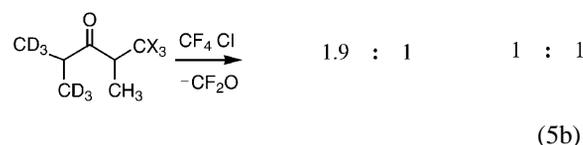
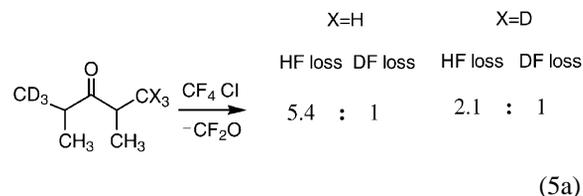


As noted above, simple elimination of HF from the metathesis ion corresponds to a small peak in the  $\text{CF}_4$  CI spectrum. In order to understand that elimination better, the  $\text{CF}_4$  CI spectrum of the monodeuterated ketone  $(\text{CH}_3)_2\text{CDCOCH}(\text{CH}_3)_2$  was explored. As in the unlabeled and dideuterated compounds, alkene elimination predominates, giving a mixture of  $\text{CH}_3\text{CH}=\text{OCF}_3^+$  ( $m/z$  113) and  $\text{CH}_3\text{CD}=\text{OCF}_3^+$  ( $m/z$  114), which together are about 10 times more abundant than the ions shown in Eq. (4). Elimination of HF from the metathesis ion ( $m/z$  98) greatly exceeds elimination of DF ( $m/z$  97), as Eq. (4) summarizes (where uncertainty corresponds to the standard error of the mean). This could result either from preferential elimination of H from a methyl group, or else from a



Scheme 1.

large kinetic isotope effect. Since the corresponding ions are virtually absent from the  $\text{CF}_4$  CI mass spectrum of  $[(\text{CH}_3)_2\text{CD}]_2\text{C}=\text{O}$ , it was necessary to look at compounds having deuterated methyl groups. With GC/MS used to separate isomers and homologues, the  $\text{CF}_4$  CI of  $[(\text{CD}_3)_2\text{CH}]_2\text{C}=\text{O}$  exhibited DF elimination to a much greater extent than HF elimination, and the latter is too weak to measure accurately.



Eqs. (5a) and (5b) summarizes the effects of perdeuterating only some of the methyl groups. The experimental HF:DF loss ratios for the two different  $\text{d}_6$  analogues do not differ significantly. These data are interpreted in terms of the competition represented in Scheme 1, where the kinetic isotope effect for eliminating a methyl deuterium has a value  $x = k_{\text{H}}/k_{\text{D}}$ . Were we to suppose that  $k = k'$  and assume an isotope effect of  $x = k_{\text{H}}/k_{\text{D}} = 1$ , this model would predict an HF-loss:DF-loss ratio of 1 for the  $\text{d}_9$  compound, a

ratio of 2 for both  $d_6$  compounds, and a ratio of 5 for the  $d_3$  compound. The experimental ratio of 5.4 for the  $d_3$  compound implies an isotope effect greater than unity, and the data lead to a value of  $k_H/k_D = 1.2 \pm 0.2$ .

The results in Eqs. (5a) and (5b) do not bear directly upon the isotope effect for Eq. (4), but isotopic substitution does have consequences with respect to the proportion of metathesis ion that is observed. Deuteration next to the carbonyl does not increase the abundance of metathesis ion; if anything, the proportion of metathesis ion decreases slightly for  $[(CH_3)_2CD]_2C=O$  relative to the unlabeled compound. By contrast, deuteration of the methyl groups increases the proportion of metathesis ion. For the  $d_6$  compounds in Eqs. (5a) and (5b), the metathesis ion abundance is about 0.025 that of  $CH_3CH=OCF_3^+$  and  $CD_3CH=OCF_3^+$  combined, more than twice what is seen for the undeuterated ketone. Since the isotopomers of  $MeCH=OCF_3^+$  are produced in statistical proportions (for instance, 50:50 for both of the  $d_6$  isomers), there is no evidence for an isotope effect on the expulsion of 2-methylbutene [10], so the relative increase in metathesis ion must be due to isotopic deceleration of DF elimination, consistent with an isotope effect  $k_H/k_D > 1$ .

Formation of the ions corresponding to loss of propene + HF +  $CF_2O$  from the  $CF_3^+$  adduct ( $m/z$  55 for unlabeled diisopropyl ketone) defies easy explanation. The methyl hydrogens apparently exchange among themselves, but do not interconvert with the other hydrogens. The only corresponding ion from  $[(CD_3)_2CH]_2C=O$  contains six deuteria ( $m/z$  61), but the ion–molecule products from the ketones shown in Eqs. (5a) and (5b) are isotopic mixtures. For  $(CH_3)_2CHCOCH(CD_3)CH_3$ , roughly equal proportions of  $d_0$ ,  $d_1$ ,  $d_2$ , and  $d_3$  ions are observed ( $m/z$  55:56:57:58 in an approximate 25:20:30:25 intensity ratio). However, complete scrambling does not take place. The two  $d_6$  analogues both display ions from  $m/z$  55 up to 61, but in quite different proportions.

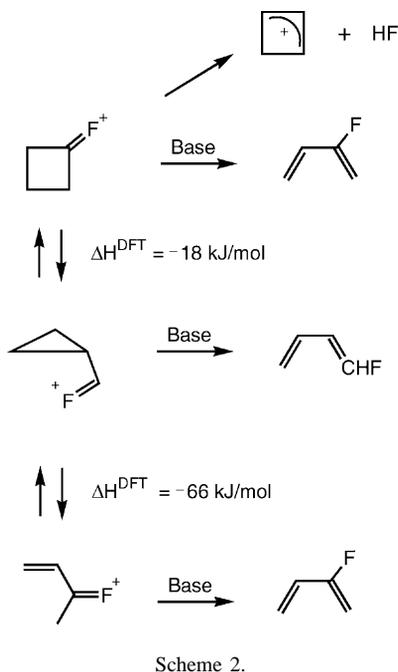
When  $CFO^+$  is the reagent ion, the dominant ion observed from  $[(CH_3)_2CH]_2C=O$  is  $m/z$  55. The alkene expulsion pathway is almost completely suppressed,

yet no metathesis ion is detected. A small amount of  $(CH_3)_2C=OCOF^+$  ( $m/z$  105, corresponding to butene loss from the  $CFO^+$  adduct) is observed (about 0.05 the abundance of  $m/z$  55), but no  $CH_3CH=OCOF^+$ . As with the reaction of diisopropyl ketone with  $CF_3^+$ , the  $m/z$  55 peak is much more intense than that of  $m/z$  97 (by about a factor of 10). The  $m/z$  55 ion subsequently transfers  $H^+$  to the parent neutral rapidly, a result that rules out the methallyl cation structure,  $H_2C=CMeCH_2^+$  (which ought to be a poor Brønsted acid).

Diethyl ketone does not exhibit metathesis ion, neither under  $CF_4$  CI conditions [5,10] nor in its reactions with  $CFO^+$ . Since loss of HF following metathesis gives an ion ( $m/z$  69) with the same nominal mass as  $CF_3^+$ ,  $(CH_3CD_2)_2C=O$  (98 at.% D) was investigated. When  $(CH_3CD_2)_2C=O$  reacts with  $CFO^+$ , the principal ions come from DF and HF loss following metathesis, in a roughly 3:1 ratio. This ratio differs markedly from what is observed in the reaction of  $(CH_3CD_2)_2C=O$  with  $CF_3^+$  in the FT-ICR spectrometer, where the ratio is approximately 1:3.5 (and the major product ion is  $CH_3CD=OCF_3^+$  from propene loss) [10]. A 1:3.5 ratio of DF:HF loss is also seen in the FT-ICR when  $C_3F_7^+$  is the reactant ion. The comparisons of  $CFO^+$  with  $CF_3^+$  demonstrate that suppressing alkene elimination does not measurably enhance the probability of seeing halonium metathesis.

### 3.3. Cyclobutanone, cyclopentanone and larger cycloalkanones

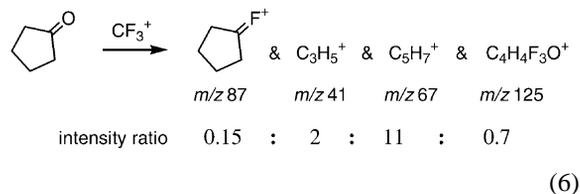
Unlike the acyclic, saturated ketones, the reaction of cyclobutanone with  $CF_3^+$  gives a measurable level of ions corresponding to metathesis,  $C_4H_6F^+$  ( $m/z$  73). Scheme 2 displays some conceivable structures for  $m/z$  73, along with their relative calculated stabilities. In the ICR (without argon relaxing gas)  $m/z$  73 is about one-eighth the intensity of the  $C_4H_5^+$  ( $m/z$  53) ion–molecule reaction product. Both  $m/z$  73 and 53 react with the parent neutral via proton transfer. This means that  $m/z$  53 cannot have the cyclobutenyl cation structure drawn at the top of Scheme 2, since removal



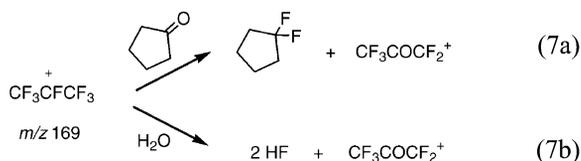
of a proton from that ion would give the notoriously antiaromatic neutral, cyclobutadiene [13]. All of the  $C_4H_6F^+$  structures shown in Scheme 2 can be deprotonated to give plausible neutral products, as shown, but none of them points to an obvious pathway for unimolecular HF loss. We note, in passing, that the favored geometry of the monofluorinated cyclopropyl-carbinyl cation (the middle structure in Scheme 2) has  $C_s$  symmetry with an *endo* orientation of the fluorine. The corresponding *exo* isomer has a calculated energy  $2 \text{ kJ mol}^{-1}$  higher.

Cyclopentanone yields a small but detectable level of metathesis ion [8]. In the FT-ICR (without any argon relaxing gas) the ion–molecule reaction of  $CF_3^+$  with cyclopentanone produces much more  $C_5H_7^+$  ( $m/z$  67) than  $C_5H_8F^+$  ( $m/z$  87), as Eq. (6) summarizes. After  $C_5H_7^+$ , the next most abundant ion–molecule reaction product is  $C_3H_5^+$  ( $m/z$  41). At a pressure of  $7 \times 10^{-9}$  Torr of cyclopentanone (with an ion gauge calibration based on a polarizability of cyclopentanone  $\alpha = 9 \text{ \AA}^3$  [14]), the measured rate of disappearance of  $CF_3^+$  corresponds to a second-order rate constant of  $2.3 \times 10^{-9} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$  in the

absence of argon relaxing gas, slightly faster than the value reported at much higher pressures [5].

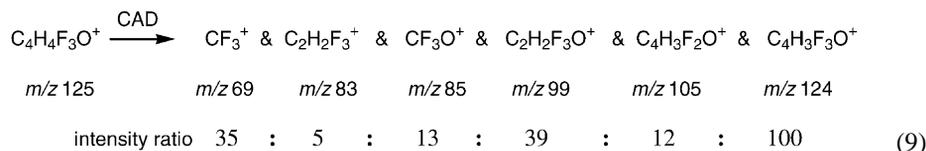


We surmised that increasing the vibrational degrees of freedom of the  $F^+$  donor would lead to internal relaxation of the metathesis product; hence,  $C_3F_7^+$  might give a higher proportion of  $C_5H_8F^+$  than does  $CF_3^+$ . Contrary to expectation, the larger ion did not give a higher yield of  $m/z$  87, although (as anticipated) the yield of  $m/z$  41 decreases to approximately one-twentieth the intensity of  $m/z$  67. The only other ion–molecule reaction product besides  $m/z$  67 was observed at  $m/z$  147 ( $C_3F_5O^+$ ), with an intensity about one-eighth that of  $m/z$  67. That product is also seen in the reactions of  $C_3F_7^+$  with every other carbonyl compound studied. While it is conceivable that the net reaction illustrated in Eq. (7a) takes place, DFT calculations predict that this double transposition is exothermic by only  $\Delta H = -30 \text{ kJ mol}^{-1}$ . It does not seem plausible that Eq. (7a) could take place without a substantial additional energy barrier, and we therefore rule it out in favor of an alternative hypothesis: namely, that the reaction is taking place between  $C_3F_7^+$  and the inevitable small amount of adventitious water (Eq. (7b)).

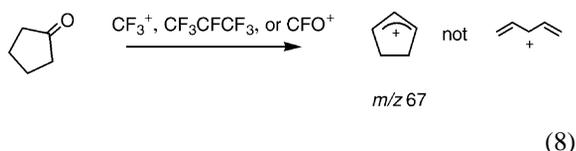


The  $C_5H_7^+$  ion goes on to react with cyclopentanone via proton transfer to give protonated parent ion ( $m/z$  85). This implicates the cyclic, allylic ion shown in Eq. (8), as opposed to the linear pentadienyl ion that would form as a consequence of electrocyclic ring opening (since the latter ion would not be acidic enough to protonate cyclopentanone). One may speculate whether making the reaction more exothermic

might lead to ring opening, so the reaction of  $\text{CFO}^+$  with cyclopentanone was also investigated. In this experiment,  $2 \times 10^{-8}$  Torr of argon was included, so as to make sure the ions from the external source were vibrationally relaxed prior to reaction. Under these



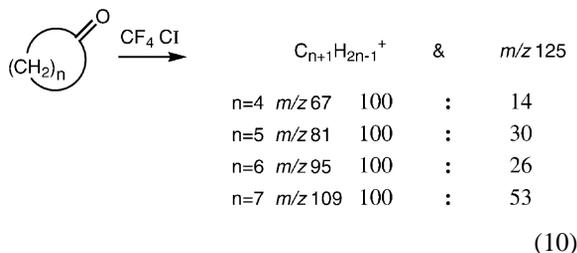
conditions  $\text{C}_5\text{H}_7^+$  was virtually the only ion–molecule reaction product, and the rate of disappearance of  $\text{CFO}^+$  corresponded to a second-order rate constant of  $1.9 \times 10^{-9} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ . The rate profile for subsequent reaction of  $m/z\ 67$  with the parent neutral to yield  $m/z\ 85$  does not appear significantly different from that of the  $\text{C}_5\text{H}_7^+$  from  $\text{CF}_3^+$  or  $\text{C}_3\text{F}_7^+$  (although the reaction was not carried out beyond the point where the  $m/z\ 67$  and  $85$  intensities are about the same). We infer that all three reactions yield predominantly (if not exclusively) the cyclic hydrocarbon ion, as Eq. (8) summarizes.



Reaction of  $\text{CF}_3^+$  with cyclopentanone yields an  $m/z\ 125$  ion, both in the FT-ICR spectrometer and (as previously reported [8]) in its  $\text{CF}_4$  CI spectrum. This ion corresponds to loss of ethylene from the  $\text{CF}_3^+$  adduct of cyclopentanone. The CAD spectrum of  $m/z\ 125$  does not display loss of  $\text{CF}_2\text{O}$  (as would be expected if it corresponded to the  $\text{CF}_3^+$  adduct of a ketone or aldehyde), but it does exhibit an  $m/z\ 69$  fragment ( $\text{CF}_3^+$ ), suggesting that group remains intact. Loss of a hydrogen atom constitutes the most intense peak, and loss of acetylene is the next most intense. Eq. (9) summarizes the principal CAD fragments, with plausible assignments as to their formulae. The same three most intense fragments are seen in the CAD spectrum of the  $m/z\ 125$  ion from  $\text{CF}_4$

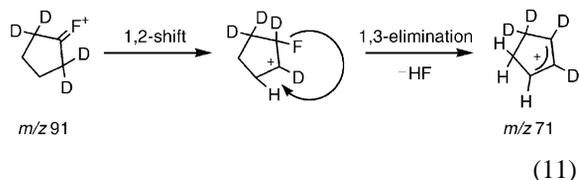
CI of  $(\text{CH}_3)_2\text{C}=\text{CHCH}=\text{O}$ , but in different proportions (an  $m/z\ 69:99:124$  intensity ratio of 3:1:10) [9]. As in the case of  $m/z\ 125$  from senecialdehyde, we surmise that the ion contains a trifluoroacetyl ( $\text{CF}_3\text{CO}$ ) group.

$\text{CF}_4$  CI of larger saturated cycloalkanones gives products similar to cyclopentanone, as Eq. (10) tabulates. For cyclohexanone ( $n = 5$ ),  $m/z\ 81$  and  $125$  give the most intense peaks. For cycloheptanone, loss of ethylene + HF ( $m/z\ 67$ ) becomes substantial (1.5 times as intense as the  $m/z\ 125$  peak). For cyclooctanone, not only is loss of ethylene + HF ( $m/z\ 81$ ) a strong peak (with nearly the same intensity as  $m/z\ 109$ ), but  $m/z\ 79$  becomes the most abundant ion (1.4 times as intense as the  $m/z\ 109$  peak). In all of these cases, the metathesis ion is visible, but very weak.



The reactions of cyclopentanone-2,2,5,5- $\text{d}_4$  were examined. As in the case of diisopropyl ketone, deuteration adjacent to the carbonyl does not increase the abundance of metathesis ion. And, as with the acyclic ketones, there are two pathways that form allylic cations, one leading to HF loss and the other to DF loss. Because the sample was only 90 atom % D, it was not possible to measure the HF:DF loss ratio with great precision, but the results are consistent with a ratio of about 5:2 for the ion–molecule reaction with  $\text{CF}_3^+$  and a ratio of about 3:1 for the reaction with  $\text{C}_3\text{F}_7^+$ . Eq. (11) illustrates a plausible mechanism for HF loss from the deuterated metathesis ion:

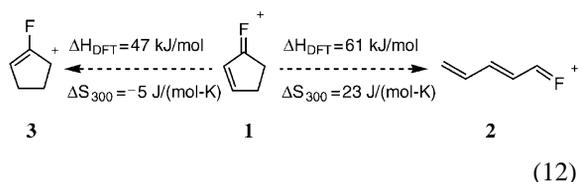
1,2-shift of a deuterium, followed by 1,3-elimination of HF to give the allylic cyclopentenyl cation.



#### 4. Discussion

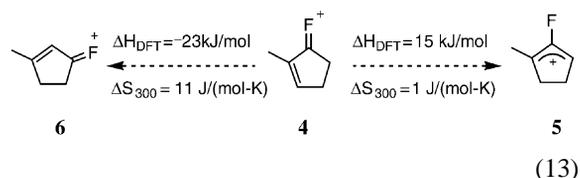
Preparing electron-deficient cations of known structure presents a challenge to gas phase ion chemists. Because of their propensity to rearrange, species for which one might logically infer a single geometry may turn out to be mixtures of isomers. Hydrocarbon ions present particular difficulties, since three-center two-electron bonds often form easily to lead to non-classical structures. One way to circumvent this is by introduction of a fluorine atom, which tends to situate the positive charge on the carbon to which fluorine is attached and to raise the energy of isomeric nonclassical ions. Another way is to introduce unsaturation, which favors allylic ions.

Halonium metathesis offers a potential route to making monofluorinated ions from ketones, but the only way to harness that technique at this point would seem to be to make sure that the desired cation corresponds to the thermodynamically favored structure. Unfortunately, all the higher homologues of acetone prefer to eliminate HF rather than retain the structure of the metathesis ion. Unsaturated ketones, however, produce ions that might turn out to have well-defined allylic structures.



To that end, this work explores the ions derived from diethyl and diisopropyl ketones, cycloalkanones, and cyclopentenone. Chemical ionization of cyclopentenone with  $\text{CF}_4$  reagent gas gives a strong  $\text{C}_5\text{H}_6\text{F}^+$  peak, to which we assign the structure of the metathesis ion (1). In part, this assignment comes from the fact that it corresponds to the thermochemical minimum for that formula. As Eq. (12) illustrates, ring opening (with the necessary hydrogen migrations) to the most stable linear ion (2; which is  $<1 \text{ kJ mol}^{-1}$  more stable than  $(\text{CH}_2=\text{CH})_2\text{C}=\text{F}^+$ ), would be very endothermic, as would isomerization to the next most favorable cyclic isomer (3).

Preparing electron-deficient cations of known structure presents a challenge to gas phase ion chemists. Because of their propensity to rearrange, species for which one might logically infer a single geometry may turn out to be mixtures of isomers. Hydrocarbon ions present particular difficulties, since three-center two-electron bonds often form easily to lead to non-classical structures. One way to circumvent this is by introduction of a fluorine atom, which tends to situate the positive charge on the carbon to which fluorine is attached and to raise the energy of isomeric nonclassical ions. Another way is to introduce unsaturation, which favors allylic ions.

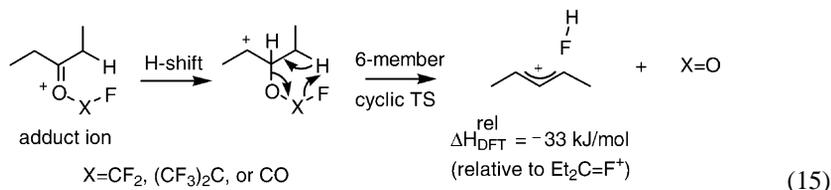


Assignment of a structure for the metathesis ion from 2-methylcyclopentanone cannot be made so confidently. As noted in Eq. (13), the expected ion, 4, is more stable than its hydrogen-shift isomers (of which the most favorable is 5), but the isomeric ion 6 is more stable than either. The type of rearrangement required to convert 4 to 6 has, as yet, no precedent in a cyclic system, but the exothermicity with which metathesis with  $\text{CF}_3^+$  forms 4 (calculated  $\Delta H = -320 \text{ kJ mol}^{-1}$ ) might make previously unknown pathways accessible.

The experimental results for deuterated diethyl ketone, diisopropyl ketone, and cyclopentanone imply that HF elimination from metathesis ions produced by  $\text{CF}_3^+$  prefer to operate via hydrogen shift followed by 1,3-elimination, as illustrated in Eq. (11). The metastable ion decomposition of the metathesis ion derived from cyclopentanone-2,2,5,5- $\text{d}_4$  gives a 2.5:1 ratio of HF:DF loss [8], which confirms this interpretation. Eq. (14) summarizes DFT calculations of the stages of this reaction, starting with the metathesis ion from diethyl ketone,  $\text{Et}_2\text{CF}^+$ . A 1,2-hydrogen shift nominally gives a secondary cation, but the DFT geometry optimization shows that it has the structure of a bridged fluoronium ion, with CF bond lengths of 1.55 and 1.68 Å. The calculated vibrational entropy of the bridged ion is virtually the

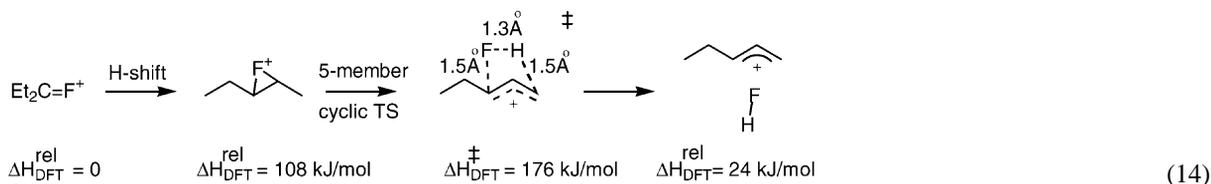
same as that of  $\text{Et}_2\text{CF}^+$ . The transition state (whose energy is given relative to  $\text{Et}_2\text{CF}^+$ ) is tighter than the bridged ion (even though the transition state has one negative force constant), with a 300 K entropy of activation of  $-15 \text{ J mol}^{-1} \text{ K}^{-1}$ . Unscaled normal modes calculations predict a zero point energy difference ( $\Delta\Delta\text{ZPE}$  between the bridged ion and transition state) of  $4.3 \text{ kJ mol}^{-1}$  between elimination of DF from a  $\text{CD}_3$  group at one end vs. elimination of HF

the 1,3-elimination transition state corresponding to the fluorine-shifted ion  $\text{CH}_3\text{CHFCH}_2\text{Et}^+$ . Since the H-shifted ion in Eq. (14) has a bridged structure, such a pathway does not strain credulity. However, the barrier height for that transition state is no higher than that of the transition state drawn in Eq. (14) (in fact, it is  $40 \text{ kJ mol}^{-1}$  lower), so elevating the reactant ion's vibrational energy content ought not to increase the proportion of apparent vicinal elimination.



from a  $\text{CH}_3$  group at the other. This is consistent with the normal isotope effect inferred for deuterated diisopropyl ketones (Eqs. (5a) and (5b)), when one takes into account the high vibrational energy content of the metathesis ions.

Eq. (15) depicts what may be a more plausible suggestion: namely, that hydrogen shift takes place in the adduct ion and that elimination via a six-member cyclic transition state then intervenes. Expulsion of



The ion–molecule reactions of deuterated diethyl ketone with  $\text{CF}_3^+$  and  $\text{C}_3\text{F}_7^+$  give 1,3-elimination of HF in preference to vicinal (or 1,2-) elimination. Vicinal HF elimination ostensibly prevails in the reaction of diethyl ketone with  $\text{CFO}^+$ . Two interpretations might account for this, which experiment alone cannot easily resolve. One alternative holds that 1,2-elimination from a hydrogen shifted metathesis ion competes with the 1,3-elimination drawn in Eq. (14) but has a higher activation energy. Since metathesis with  $\text{CFO}^+$  is much more exothermic than with  $\text{CF}_3^+$  or  $\text{C}_3\text{F}_7^+$ , that hypothesis would explain the reversal of preference in terms of a greater vibrational energy content for the  $\text{CFO}^+$  metathesis product. DFT calculations, however, do not support this picture. Repeated efforts to locate a vicinal elimination transition state result (at best) in

CO from the  $\text{CFO}^+$  adduct would leave behind the HF complex of 1,3-dimethylallyl cation. While HF expulsion via a four-center transition state occurs in the metathesis ion from acetone [8,15], 1,2-elimination might never take place in the metathesis ion from diethyl ketone (regardless of whether hydrogen shift takes place). The difference between  $\text{CF}_3^+$  or  $\text{C}_3\text{F}_7^+$ , on the one hand, and  $\text{CFO}^+$  on the other could reflect the extent to which six-center elimination occurs in the adduct ions.

Finally, we consider the transition state for halonium metathesis with  $\text{CF}_3^+$ . DFT calculations have shown that the barrier heights for saturated carbonyl compounds do not exhibit any correlation with the overall thermochemistry of the F<sup>+</sup> for O interchange. As Table 1 summarizes, the same is true for the conjugated aldehydes and ketones.

Table 1

DFT enthalpy changes (0 K) and activation barriers for metatheses of unsaturated carbonyl compounds with  $\text{CF}_3^+$  (relative to the 0 K heat of formation of the gaseous  $\text{CF}_3^+$  adduct)

Unsaturated carbonyl compound	$\Delta H$ ( $\text{kJ mol}^{-1}$ )	$\Delta H^\ddagger$ ( $\text{kJ mol}^{-1}$ )
$\text{H}_2\text{C}=\text{CHCH}=\text{O}$	-228	184
$\text{H}_2\text{C}=\text{C}(\text{CH}_3)\text{CH}=\text{O}$	-257	190
$\text{H}_2\text{C}=\text{CHCOCH}_3$ ( <i>trans-cis</i> conformation)	-288	172
2-Cyclopentenone	-307	207
$(\text{CH}_3)_2\text{C}=\text{CHCH}=\text{O}$	-317	211
Z- $\text{CH}_3\text{CH}=\text{CHCOCH}_3$ ( <i>trans-cis</i> conformation)	-314	190

The schematic potential energy surface in Fig. 1 exemplifies the general sequence of steps for an exothermic metathesis. The central barrier is much lower than the energy of the entrance channel but is comparable to the energy of the exit channel. The position of the transition state along the reaction coordinate changes

with the neutral reactant in a regular fashion as a function of the net exothermicity. As Fig. 2 summarizes for saturated aldehydes and ketones, the four bond lengths in the four-member ring vary linearly with the overall  $\Delta H$ , which ranges from slightly endothermic in the case of hexafluoroacetone to  $-269 \text{ kJ mol}^{-1}$  for cyclohexanone [8]. Ring strain has only a slight effect, as witness the bond lengths for metathesis of cyclopentanone.

As the metathesis becomes more exothermic the transition state looks more like the product. On the face of it, such behavior would appear to contradict the Hammond postulate [13], but (as we have discussed elsewhere [8]) it is, in fact, consistent with the Hammond postulate. The  $\text{CF}_3^+$  adduct of the starting material represents the potential energy minimum along the reaction coordinate. An exothermic metathesis corresponds to an endothermic isomerization of the  $\text{CF}_3^+$  adduct to a complex of  $\text{CF}_2\text{O}$  with the fluoroalkyl cation. As illustrated

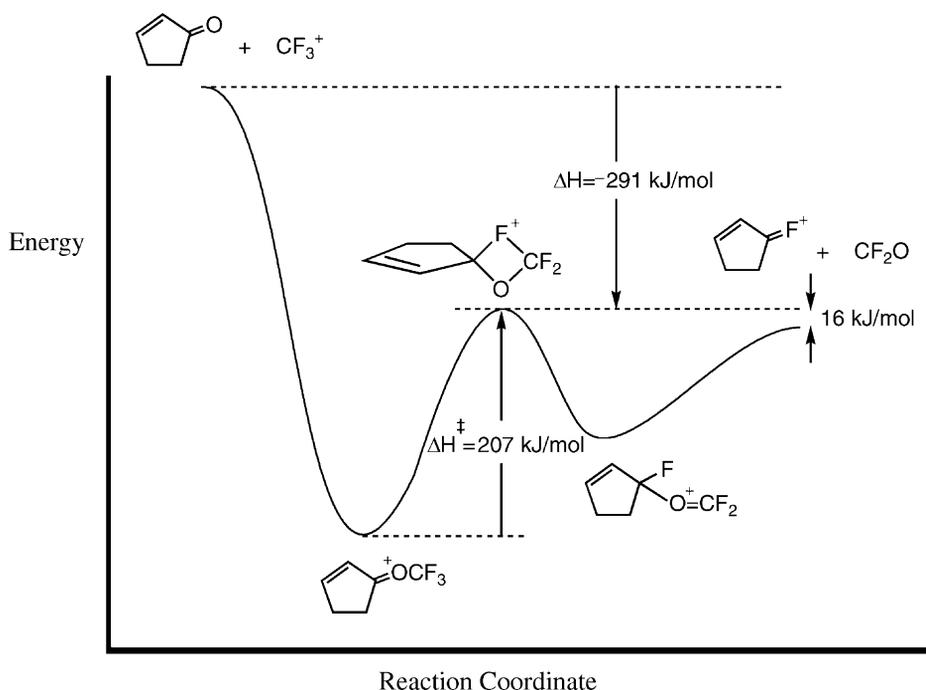


Fig. 1. Schematic potential energy surface for metathesis of 2-cyclopentenone with  $\text{CF}_3^+$  showing DFT 0 K enthalpy differences calculated at B3LYP/6-311G\*\*.

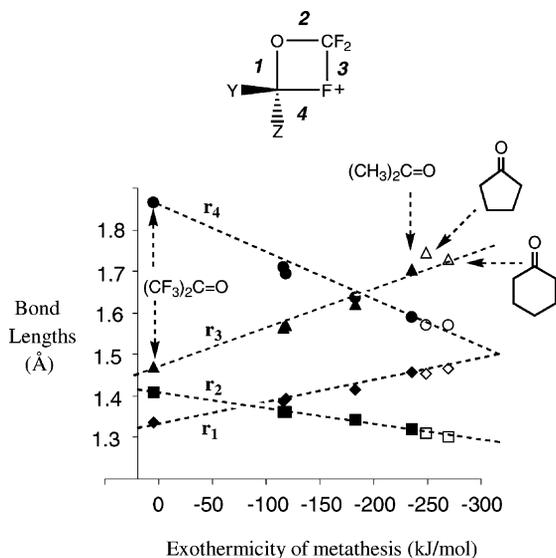


Fig. 2. Distances for the CO ( $r_1$ , diamonds), OCF<sub>2</sub> ( $r_2$ , squares), FCF<sub>2</sub> ( $r_3$ , triangles), and CF ( $r_4$ , circles) bonds in DFT-calculated (6-31G\*\* basis set) metathesis transition states for five acyclic ketones and aldehydes (filled symbols) and two cycloalkanones (open symbols) [8].

in Eq. (16) for an arbitrary carbonyl compound, isomerization of the adduct is energetically uphill (step *ii*) when the overall transposition has  $\Delta H < 0$  for the sum of all three steps. The bond lengths in the transition state reflect the energetic ordering within the attractive ion–molecule potential, whose trend runs opposite to the net exothermicity of the ion–molecule reaction.

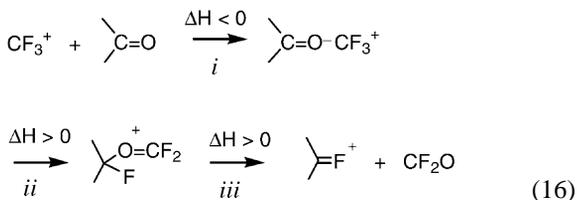


Fig. 3 demonstrates that unsaturated aldehydes and ketones exhibit the same behavior as do saturated carbonyl compounds, but with different slopes than for the compounds in Fig. 2. In terms of Fig. 1, the top of the barrier shifts to the right as the overall  $\Delta H$  becomes more negative. The orderliness of the variations exhibited in Fig. 3 contrasts with the almost haphaz-

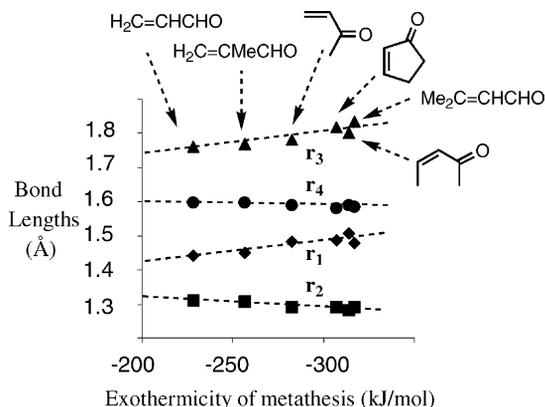


Fig. 3. Distances for the CO ( $r_1$ , diamonds), OCF<sub>2</sub> ( $r_2$ , squares), FCF<sub>2</sub> ( $r_3$ , triangles), and CF ( $r_4$ , circles) bonds in DFT-calculated (6-311G\*\* basis set) metathesis transition states for acrolein, methacrolein, methyl vinyl ketone, cyclopentenone, and Z-3-penten-3-one in its *trans-cis* conformation.

ard relationship between  $\Delta H^\ddagger$  and  $\Delta H$  summarized in Table 1.

## 5. Conclusions

Halonium metathesis is a high barrier ion–molecule reaction, which is made possible by the enormous exothermicity of attachment of fluorinated cations to carbonyl oxygens in the gas phase. Because  $\Delta H$  is so negative for the overall transposition of F<sup>+</sup> for O as well as for the initial attachment, a variety of other reactions limit its yield. In many cases, rearrangement and fragmentation of the adduct ions occur to the virtual exclusion of metathesis. In other cases, the metathesis ions subsequently decompose. Finally, unless the metathesis ion corresponds to a global minimum on the potential energy surface, one must suspect that a mixture of isomeric ions is formed. Appropriate deuterium substitution can increase the efficiency of metathesis measurably, but not enough to harness it for practical purposes.

From a theoretical standpoint, halonium metathesis is a well behaved reaction, in the sense that it appears to obey the Hammond postulate. This implies that computational methods can predict conditions where

F<sup>+</sup> for O interchange should succeed. In the present instance, the high yield from 2-cyclopentenone (Eq. (3)) attests to the capacity of computation to augment intuition in predicting how metathesis can be tamed.

### Acknowledgements

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