

Computational Studies of Oxahalocarbene Fragmentation: Convergence of Theory and Experiment

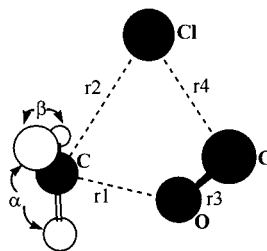
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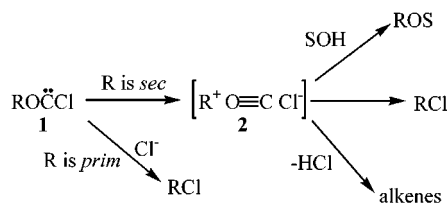
ABSTRACT



B3LYP/6-31G* computed transition states and activation energies for the unimolecular and bimolecular fragmentation reactions of eight oxahalocarbenes (ROCX) are in good accord with the available experimental structure–reactivity behavior, supporting and amplifying the current mechanistic conception of these reactions.

The fragmentation of oxachlorocarbenes (ROCCl, **1**) unites aspects of carbene, carbocation, elimination, and substitution chemistry.¹ When R is a *sec*-alkyl group, fragmentation to an ion pair (**2**) and products derived therefrom appears from experiment to be the dominant fate of **1**; cf., Scheme 1.²

Scheme 1



However, when R is primary, “unimolecular” fragmentation to a primary cation is less favorable than S_N2-like “bimolecular” fragmentation.³ There are strong analogies in

structure–reactivity behavior between these CO-eliminative carbene fragmentations and the N₂-eliminative reactions of diazonium ions,⁴ the SO₂-eliminative decompositions of alkyl chlorosulfites,⁵ and the CO₂-eliminative reactions of alkyl chloroformates.⁶

Although the more common carbenic reactions, such as addition to alkenes⁷ and 1,2-H migrations,⁸ have been subjected to many computational studies, no such examina-

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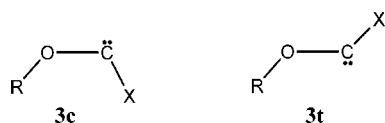
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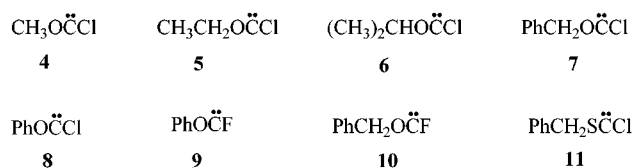
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tion has been made of oxahalocarbenes fragmentation. Here we present some initial results of our ongoing analysis which afford remarkable congruence with experimental results. This agreement strongly supports the current mechanistic paradigm of these carbene fragmentation reactions.

Alkoxy- and aryloxyhalocarbenes can exist in cis (**3c**) or trans (**3t**) forms, in which interconverting rotation about the O–C bond is restricted by partial double bond character (R–O⁺=C⁻–Cl).⁹ We sought B3LYP/6-31G* transition states for the fragmentations of eight examples of **3c** and four isomeric carbenes, **3t**. The carbenes included methoxychloro-



rocarbenes (**4c** and **4t**), ethoxychlorocarbenes (**5c** and **5t**), isopropoxychlorocarbenes (**6c** and **6t**), benzyloxychlorocarbenes (**7c** and **7t**), phenoxychlorocarbenes (**8c**), phenoxyfluorocarbenes (**9c**), benzyloxyfluorocarbenes (**10c**), and benzythiochlorocarbenes (**11c**).



All structures were fully optimized by analytical gradient methods at the B3LYP/6-31G* level using the Gaussian94¹⁰ suite of programs. Reported gas-phase energies (unscaled) were corrected for thermal effects at 298.15 Kelvin and for zero-point energy differences. Normal coordinate analyses confirmed the nature of the ground and transition structures.

Due to convergence problems, it was not possible to do full optimizations using the SCI-PCM model with few exceptions (see tables). Instead, single-point determinations were carried out using gas-phase geometry. An intrinsic reaction coordinate (IRC) calculation confirmed that the gas-phase transition structure located for the methyl system **4c** led to the expected products: methyl chloride and carbon monoxide. ZPE corrections were evaluated from the gas-phase results and were in the range of 2.5 ± 1.5 kcal/mol.

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Transition states for fragmentation were located for the eight cis carbenes in the gas phase but could not be found for the four trans carbenes. Fully optimized B3LYP/6-31G* transition states for the fragmentations of, for example, **4c**–**7c** appear in Figure 1, and the associated interatomic

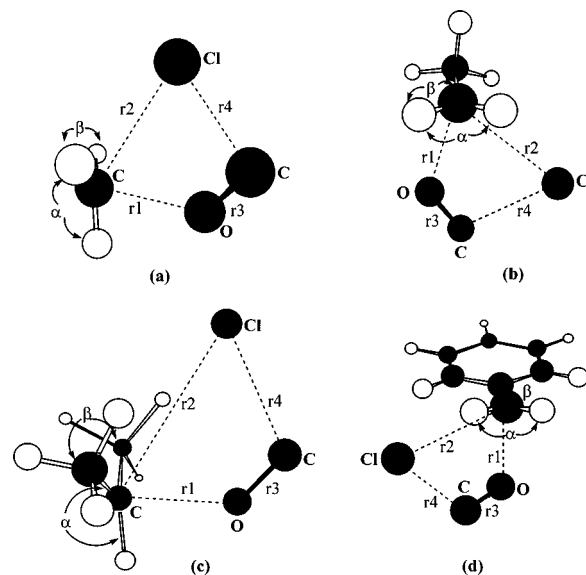


Figure 1. B3LYP/6-31G* transition states for the gas-phase fragmentations of (a) **4c**, (b) **5c**, (c) **6c**, and (d) **7c**.

separations ($r1$ – $r4$) and bond angles (α and β), as defined in Figure 1, are collected in Table 1.

Table 1. Interatomic Separations and Bond Angles of Carbene Fragmentation Transition States^a

carbene	$r1^b$	$r2^b$	$r3^b$	$r4^b$	α^c	β^c
4c	2.181	2.796	1.176	2.338	119.1	118.3
5c	2.277	3.102	1.162	2.589	117.7	120.9
6c	2.101	3.580	1.176	2.456	118.5	120.5
7c	2.200	3.349	1.173	2.396	118.5	120.3

^a B3LYP/6-31G* structures optimized in the gas phase; cf. Figure 1. ^b In angstroms. ^c In degrees.

In these transition states, strong interactions clearly exist between the nascent chloride anions and the cationic carbons: $r2$ is between 2.8 and 3.6 Å. For the trans carbenes (**3t**), where this interaction is impossible, fragmentation transition states could not be located. Clearly, fragmentation in the cis series of carbenes (**3c**) should afford “tight” (R^+Cl^-) ion pairs, as suggested by experiment.^{1,2a,11} Furthermore, the fragmentations are advanced at the cationic centers, where the C–O separations ($r1$) are 2.1–2.3 Å and the bond angles approach 120° (i.e., planarity). The

(11) Moss, R. A.; Ho, G. J.; Wilk, B. K. *Tetrahedron Lett.* **1989**, *30*, 2473. In the limit, the mechanism approaches a classical S_N1 process.⁵

carbon monoxide leaving group (r_3 , 1.16–1.18 Å) is en route to the C=O bond length of 1.128 Å.

The computed activation energies for the fragmentations of **4c–11c** appear in Table 2. We also include activation

Table 2. Computed Activation Energies for Fragmentations of ROCX

carbene	R	X	E_a^{gas} ^a	E_a^{soln} ^b
4c	Me	Cl	33.2	30.1
5c	Et	Cl	25.5	17.9
6c	Me ₂ CH	Cl	9.24	7.96
7c	PhCH ₂	Cl	6.71	1.45
8c	Ph	Cl	32.7	32.8
9c	Ph	F	41.8	43.0
10c	PhCH ₂	F	27.1	27.0
11c	PhCH ₂ S ^c	Cl	46.4	34.3
4t	Me	Cl	190.5 ^d	50.6 ^d
5t	Et	Cl	151.1 ^d	24.9 ^d
6t	Me ₂ CH	Cl	131.8 ^d	11.8 ^d
7t	PhCH ₂	Cl	109.4 ^d	−0.5 ^d

^a B3LYP/6-31G* with zero-point energy correction (gas phase). In kcal/mol. ^b Self-consistent isodensity polarized continuum model (SCI-PCM) in simulated MeOH ($\epsilon = 32.6$). In kcal/mol. The SCI-PCM transition state was located for **4c** and **9c**; other entries refer to single-point calculations based on the optimized gas-phase structures. Single-point E_a^{soln} values for **4c** and **9c** transition states were very similar to the fully optimized values, 31.5 and 43.0 kcal/mol, respectively. ^cPhCH₂SCCl. ^dEnergy difference between carbene and fragments (R⁺ OC Cl[−]) in the gas phase or in MeOH.

energies for fragmentations occurring in a simulated polar solvent (e.g., MeOH, $\epsilon = 32.6$), computed with the B3LYP/6-31G* self-consistent isodensity polarized continuum model (SCI-PCM). Because transition states could not be located for the trans carbenes **4t–7t**, we list the energy differences between the ground-state carbenes and their fragmentation products (R⁺, CO, Cl[−]).

A very satisfying congruence emerges between trends in the computed activation energies (Table 2) and the observed fragmentation behavior of ROCX. The sharp decrease for the computed (solution) E_a from MeOCCl (30 kcal/mol) to PhCH₂OCCl (1.5 kcal/mol) is in accord with the persistence of MeOCCl in solution,¹² compared to the rapid fragmentation of PhCH₂OCCl to an ion pair and the latter's subsequent solvolysis.¹³ With $E_a \sim 18$ kcal/mol, *cis*-EtOCCl is much more likely than MeOCCl to fragment unimolecularly in a polar solvent, but our results (see below) suggest that bimolecular, S_N2-like fragmentations with Cl[−] or, for

example, MeOH are even more likely. The S_N2 pathway is experimentally observed with primary ROCCl (e.g., *n*-BuOCCl).³ For *sec*-ROCCl, such as *i*-PrOCCl, the low computed E_a makes likely unimolecular fragmentation to an ion pair in MeOH or MeCN, similar to the behavior of PhCH₂OCCl. Experimental studies of 2-BuOCCl in polar solvents agree with this conclusion.^{2a} Furthermore, the computed E_a values for the (gas phase) fragmentations of (*cis*) MeOCCl, EtOCCl, *i*-PrOCCl, and PhCH₂OCCl afford a good linear correlation (slope = 0.35, $r = 0.97$) with the experimental hydride affinities of the corresponding carbocations,¹⁴ suggesting that the stability of the nascent carbocation forming in the fragmentation is a key factor in determining the E_a .

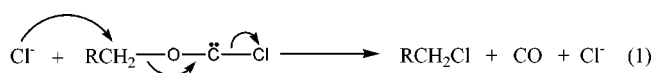
The phenoxyhalocarbenes **8** and **9** should resist fragmentation to avoid putting positive charge on a phenyl carbon. Indeed, both carbenes are computed to have $E_a > 30$ kcal/mol (Table 2) and both are persistent in solution.^{15,16} Our computed E_a for the gas-phase fragmentation of PhOCCl (~ 33 kcal/mol) is relatively close to the computed E_a for the related conversion of the benzenediazonium ion to Ph⁺ and N₂ (26.6 kcal/mol).¹⁷

The additional energy required to break a C–F bond versus a C–Cl bond is apparent in the computed E_a values for PhOCF and PhOCCl (Table 2) and is even more striking on comparison of PhCH₂OCF (**9c**) with PhCH₂OCCl (**7c**). The latter fragments readily in solution,¹³ but PhCH₂OCF is persistent and readily intercepted by alkenes or methanol.¹⁸ In a similar vein, the high heat of formation of CS, relative to CO (+234 vs −110.5 kcal/mol) contributes to the high E_a computed for the fragmentation of PhCH₂SCCl (46 kcal/mol, gas phase), relative to PhCH₂OCCl (6.7 kcal/mol). PhCH₂SCCl is thus predicted to be a persistent carbene.

We could not locate transition states for the fragmentations of *trans*-ROCCl (**4t–7t**). Gas-phase fragmentations of these species are highly endothermic (Table 2) because the developing R⁺ and Cl[−] cannot interact. In MeOH (or MeCN), ion solvation greatly reduces the fragmentation enthalpies, and at least (*trans*) Me₂CHOCCl and PhCH₂OCCl might fragment. We have previously suggested that *trans*-ROCCl predominantly afford solvolysis products (probably by S_N2 processes³) relative to *cis*-ROCCl, which are ideally constituted to yield RCl via ion pair collapse.^{1,13}

Activation energies for *cis*–*trans* isomerizations (**3c** ⇌ **4c**) via carbene–oxygen bond rotation are all computed to be ~ 15 – 18 kcal/mol, in either solution or the gas phase, for MeOCCl, EtOCCl, or *i*-PrOCCl. For *trans*-MeOCCl or *trans*-EtOCCl, where $E_a(\text{frag})$ is high, unimolecular fragmentation could proceed via initial isomerization to the *cis* carbene. However, at least in polar solution, *trans*-*i*-PrOCCl could fragment directly, because the required E_a is only ~ 12 kcal/mol (Table 2). Bimolecular substitution/fragmentations of all three *trans* carbenes could proceed directly.

Thus, we observed that primary ROCCl are subject to very facile S_N2 reactions with Cl[−] in MeCN solution,³ eq 1. We



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located transition states in the gas phase and in MeOH (SCI-PCM) for the chloride-induced S_N2 fragmentations of (*cis* and *trans*) MeOCCl, EtOCCl, and (*trans*) *i*-PrOCCl, as well as the S_N2 -methanolysis of *trans*-EtOCCl. Further details of these calculations will appear in our full paper, but Figure 2

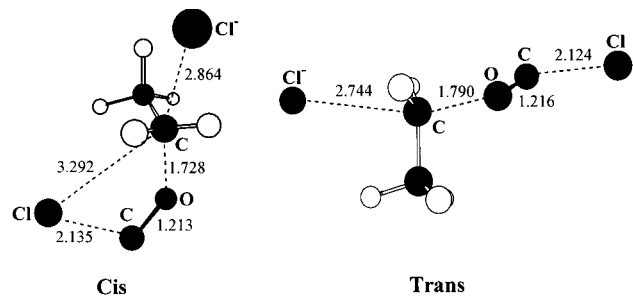


Figure 2. S_N2 gas-phase transition states of EtOCCl with Cl^- , distances (in Å). The attacking chloride is labeled Cl^- .

presents as examples the fully optimized gas-phase transition states for the EtOCCl/ Cl^- reactions, while Table 3 collects computed activation energies for the S_N2 displacement/fragmentation steps in simulated MeOH.

Table 3. Computed Activation Energies for S_N2 Fragmentations of ROCCl^a

carbene	R in ROCCl	E_a^{soln} ^b (kcal/mol)
4c	Me	2.86 ^c
4t	Me	5.13 ^c
5c	Et	3.71 ^d
5t	Et	4.53 ^c
5c^e	Et	7.12 ^d
5t^e	Et	7.38 ^d
6t	Me ₂ CH	7.43 ^d

^a With Cl^- as nucleophile, unless otherwise indicated. ^b B3LYP/6-31G* SCI-PCM calculations in simulated MeOH. ^c SCI-PCM calculations are fully optimized. ^d SCI-PCM calculations are single points based on optimized gas-phase structures. ^e The nucleophile is MeOH.

Comparisons of the interatomic separations of the S_N2 fragmentation transition states (Figure 2) with those of the

“unimolecular” fragmentations (Table 1) reveal that the former are “tighter”, with less developed R- -O and C- -Cl separations. For *cis*-EtOCCl, for example, the carbenic C-O and C-Cl transition state separations are 2.28 and 2.59 Å, respectively, for unimolecular fragmentation, but 1.73 and 2.13 Å for bimolecular fragmentation.

More importantly, the computed E_a values for the S_N2 fragmentations in solution (Table 3) are uniformly lower than those of the corresponding unimolecular fragmentations (Table 2). Note particularly the EtOCCl cases, **5c** and **5t**, where the unimolecular E_a values of ~18 and ~25 kcal/mol drop to ~7 kcal/mol for S_N2 fragmentations. Indeed, for *trans*-EtOCCl + Cl^- , the B3LYP(SCI-PCM)/6-31G* E_a , corrected for zero-point energy, is 3.9 kcal/mol, with $\Delta S^\ddagger = -19.1$ eu (25 °C). These parameters are in remarkable agreement with the experimental values of $E_a = 3.1$ kcal/mol and $\Delta S^\ddagger = -21.8$ eu for the S_N2 fragmentation of *n*-BuOCCl.³ Clearly, for EtOCCl, and by extension other simple primary ROCCl, S_N2 fragmentation with Cl^- is energetically preferable to unimolecular fragmentation. This agrees with experimental findings for *n*-BuOCCl and *i*-BuOCCl.³ On the other hand, the unimolecular decompositions of PhCH₂OCCl (**7c** and **7t**) traverse such low computed barriers (Table 2) that they are likely to remain S_N1 , even in the presence of Cl^- , a prediction that is in agreement with experiments which show the dependence of k_{frag} on chloride concentration to be small.³

Finally, we note that the methanolysis reactions of EtOCCl are also likely to be S_N2 (Table 3), as is the chloride-induced decomposition of *trans*-*i*-PrOCCl **6t**. The E_a values for S_N1 and S_N2 (Cl^-) fragmentations of **6t** are not very different (11.8 and 7.4 kcal/mol, respectively), so the precise experimental conditions and chloride concentration will be mechanistically decisive.

In summary, we find that B3LYP/6-31G* calculations of unimolecular and bimolecular oxahalocarbene fragmentation reactions provide transition states and activation energies that very satisfactorily accord with the experimentally defined structure–reactivity behavior of these unusual reactions.

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