Carbenes as Substrates: Bimolecular Fragmentation of Alkoxychlorocarbenes

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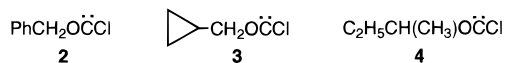
Abstract: Fragmentation reactions of *n*-butoxychlorocarbene (**9**), isobutoxychlorocarbene (**10**), and benzyloxychlorocarbene (**2**) were studied by product analysis and by laser flash photolysis (LFP). The carbenes were generated photochemically from 3-alkyl-3-chlorodiazirines in (1) MeCN solution; (2) 5.77 M pyridine in MeCN; (3) 0.504 M tetrabutylammonium chloride (Bu$_4$NCl) in MeCN; or (4) 5.77 M pyridine + 0.504 M Bu$_4$NCl in MeCN. In MeCN, **9** gave mainly HCl-capture product, *n*-butyl dichloromethyl ether (45.1%), carbene dimer (9.8%), and azine (14.6%). Fragmentation products 1-butene (14.4%), 2-butyl chloride (6.0%), and 1-butyl chloride (10.2%) were limited. With added pyridine, HCl was scavenged, the dichloromethyl ether was suppressed, and 1-butene (42.1%), 2-butyl chloride (7.3%), and 1-butyl chloride (24.1%) were dominant. With added Bu$_4$NCl, 1-butyl chloride increased to 46.4%. With both pyridine and Bu$_4$NCl, 1-butyl choride was 63% of the product, with 1-butene at 22.8%. A similar pattern was observed with carbene **10**. Products in MeCN included isobutene (23%), 1- and 2-butene (8−9%), *tert*-butyl chloride (1.7%), 2-butyl chloride (5.8%), isobutyl chloride (0.4%), isobutyl dichloromethyl ether (53%), and carbene dimer (8%). The isobutyl chloride fragmentation product increased from 0.4% in MeCN, to 7.3% with pyridine, to 32% with Bu$_4$NCl, and to 38% with both addends. With **2**, benzyl chloride increased from 83% in MeCN to 91% with added pyridine and Bu$_4$NCl. The increases in chloride displacement products are attributed to bimolecular attacks of chloride ions at the α-carbon atoms of the carbenes, particularly **9** and **10**. LFP kinetic studies show that the rate constants for fragmentations of these carbenes increase linearly with the concentration of added Bu$_4$NCl in pyridine−MeCN. Second-order rate constants (k_2) as a function of [Cl$^-$] (M^{-1} s^{-1}, 24 °C) for the fragmentations are 8.2 × 10^6 (**9**), 2.7 × 10^6 (**10**), and 2.2 × 10^6 (**2**). The decrease in k_2 as R in ROCCl changes from *n*-butyl to isobutyl to benzyl is in accord with a S$_N$2-like mechanism for the carbene fragmentations in which the benzyl case involves the competitive incursion of S$_N$1-like fragmentation.

Decades ago, Hine[1] and Skell[2] discovered that alkoxyhalocarbenes (**1**) formed upon reaction of dihalocarbenes with alkoxide ions, and Skell observed that these "derived" carbenes fragmented to alkyl cations with loss of halide and carbon monoxide,[2] eq 1. Unfortunately, the requirement for strong base

$$RO^- + :CX_2 \longrightarrow ROCX_2^- \xrightarrow{-X^-} RO\ddot{C}X \longrightarrow R^+ + CO + X^- \quad (1)$$
$$\mathbf{1}$$
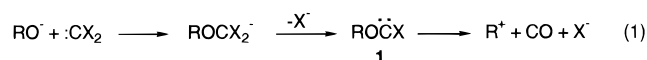
in this "deoxideation"[2] reaction limits its utility as a means of generating carbocations. Subsequently, however, Smith and Stevens found that 3-methoxy- and 3-isobutoxy-3-chlorodiazirines afforded the corresponding alkoxychlorocarbenes upon thermolysis; fragmentation of the carbenes could be studied under neutral conditions.[3]

We extended this methodology to studies of benzyloxychlorocarbene (**2**),[4] cyclopropylmethoxychlorocarbene (**3**),[5] and 2-butoxychlorocarbene (**4**).[6] Product and stereochemical studies

$$PhCH_2O\ddot{C}Cl \qquad \triangleright\!\!-CH_2O\ddot{C}Cl \qquad C_2H_5CH(CH_3)O\ddot{C}Cl$$
$$\mathbf{2} \qquad\qquad \mathbf{3} \qquad\qquad\qquad \mathbf{4}$$

were most easily rationalized according to a mechanistic scheme in which the alkoxychlorocarbenes fragmented to alkyl chlorides, alkenes, and solvolysis products via ion pairs (**5**); eq 2.[4−6] In particular, with R = PhCHD, return of Cl$^-$ occurred with

$$ROCCl \xrightarrow{MeCN} [\, R^+ \, O\!\equiv\!C \, Cl^- \,] \longrightarrow \text{Products} \quad (2)$$
$$\mathbf{1} \qquad\qquad\quad \mathbf{5}$$
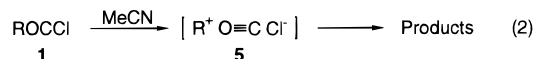
60−80% net retention.[4b] When R = 2-butyl, chloride return involved 56% net retention, while solvolysis in 1-butanol afforded 2-chlorobutane by chloride return (82% net retention) and 2-butyl 1-butyl ether by solvolysis (71% net inversion).[6] Finally, with R = cyclopropylmethyl, typical cyclopropylmethyl cation rearrangement products were formed in distributions consistent with the intermediacy of ion pairs.[5]

More recently, we have been able to measure the absolute kinetics of several carbene fragmentation reactions, eq 2, by laser flash photolysis (LFP).[7] For benzyloxychlorocarbene (**2**), 1-adamantylmethoxychlorocarbene (**6**), and neopentoxychlorocarbene (**7**), fragmentation rate constants (k_{frag}, s^{-1}) were 0.69 × 10^6 to 1.3 × 10^6, 2.8 × 10^6 to 5.2 × 10^6, and 0.3 × 10^6 to

(1) Hine, J.; Pollitzer, E. L.; Wagner, H. *J. Am. Chem. Soc.* **1953**, *75*, 5607.

(2) Skell, P. S.; Starer, I. *J. Am. Chem. Soc.* **1959**, *81*, 4117.

(3) (a) Smith, N. P.; Stevens, I. D. R. *J. Chem. Soc., Perkin Trans. 2* **1979**, 1298. (b) Smith, N. P.; Stevens, I. D. R. *J. Chem. Soc., Perkin Trans. 2* **1979**, 213.

(4) (a) Moss, R. A.; Wilk, B. K.; Hadel, L. M. *Tetrahedron Lett.* **1987**, *28*, 1969. (b) Moss, R. A.; Kim, H.-R. *Tetrahedron Lett.* **1990**, *31*, 4715.

(5) Moss, R. A.; Ho, G.-J.; Wilk, B. K. *Tetrahedron Lett.* **1989**, *30*, 2473.

(6) Moss, R. A.; Balcerzak, P. *J. Am. Chem. Soc.* **1992**, *114*, 9386.

(7) Moss, R. A.; Ge, C.-S.; Maksimovic, L. *J. Am. Chem. Soc.* **1996**, *118*, 9792.

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Table 1. Fragmentations of *n*-Butoxychlorocarbene (**9**)[a]

Solvent	$\sim\!\!\sim$	$\overset{\curlyvee}{\text{Cl}}$	$\sim\!\!\sim$Cl	$\sim\!\!\sim$O$\frown$Cl$_2$H	dimer	azine
MeCN	14.4	6.0	10.3	45.1	9.7	14.5
0.5 M Cl⁻-b	44.2	8.2	21.5	3.1	9.0	14.0
5.8 M pyr-c	23.8	4.4	46.4	9.0	9.3	7.1
5.8 M pyr-c 0.5 M Cl⁻-b	22.8	3.2	63.3	3.3	3.4	4.0

[a] All experiments in MeCN solvent at 25 °C. Values are percentages of the total products formed. [b] Cl⁻ added as *n*-Bu$_4$N⁺Cl⁻. [c] pyr = pyridine.

1.3×10^6, respectively.[7,8] The unexpectedly rapid fragmenta-

tions of primary alkoxychlorocarbenes **6** and **7**, coupled with rearranged alkyl groups in their products, suggested that the fragmentations could have been concerted with alkyl participation.[7,9]

Now we describe the unexpectedly facile fragmentation reactions of *n*-butoxychlorocarbene and isobutoxychlorocarbene, which we believe are novel examples of bimolecular carbene fragmentation, i.e, S_N2 reactions in which the carbenes are substrates for nucleophilic chloride attack at their α-carbons, rather than at their carbenic centers.

Results and Discussion

Reactions and Products. Diazirine precursors, **8**, for carbenes **9**, **10**, and **2** were prepared by hypochlorite oxidations[10] of the appropriate *O*-alkylisouronium tosylates, **11**.[3,4] The latter were prepared by reactions of *n*-butyl alcohol, isobutyl alcohol, or benzyl alcohol with cyanamide and anhydrous *p*-toluene-sulfonic acid in dry chloroform.[3a,4a] The diazirines were purified
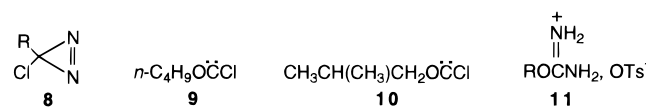
by column chromatography over silica gel with pentane, and then "transferred" to MeCN solution (see Experimental), where they exhibited λ_{max} 356 nm.

Photolysis ($\lambda > 320$ nm) of **8** (R = *n*-Bu) at 25 °C in MeCN ($A_{356} = 1.0$) gave 1-butene, 2-chlorobutane, dichloromethyl ether **12** (R = Bu), carbene dimer, and azine **13** (R = Bu). Product
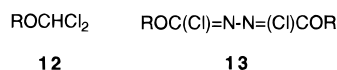
distributions were obtained by capillary GC, while product identities were confirmed by GC-MS or GC comparisons with authentic materials; a summary appears in Table 1.

In MeCN, *n*-butoxychlorocarbene (**9**), generated photochemically from diazirine **8**, affords mainly dichloride **12**, carbene dimer, and azine **13**. The dichloride is at least partly an HCl capture product,[7] although not enough 1-butene is produced to account for all of the dichloride. Conceivably, the 1-butene is underanalyzed due to its volatility, and/or some HCl is generated during uncharacterized "polymer formation".

(8) The ranges cited for the rate constants reflect alternative methods of data analysis.[7]

(9) Liggero, S. H.; Sustmann, R.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1969**, *91*, 4571. Sanderson, W. A.; Mosher, H. S. *J. Am. Chem. Soc.* **1966**, *88*, 4185.

(10) Graham, W. H. *J. Am. Chem. Soc.* **1965**, *87*, 4396.

In MeCN alone, unrearranged fragmentation substitution and elimination products, 1-BuCl and 1-butene, account for only 25% of product, while H-shift product 2-BuCl contributes 6%. However, with 0.5 M added chloride (as *n*-Bu$_4$N⁺Cl⁻), there is a 4-fold increase in 1-BuCl and a 5-fold decrease in HCl capture of the carbene; fragmentation products 1-butene, 1-BuCl, and 2-BuCl total 75%. With 5.77 M added pyridine (mimicking LFP conditions; see below), HCl is scavenged, product **4a** is suppressed, and fragmentation accounts for ~74% of the products. Here, primary "displacement" to 1-BuCl is twice that in MeCN alone, while elimination (E2?) product 1-butene rises to 42%. Finally, with *both* added Cl⁻ and pyridine, 1-BuCl is the major product (63%) and fragmentation (89%) is the principal fate of carbene **1a**. The sensitivity of the product distributions to added Cl⁻ suggests direct nucleophilic attack on the carbene or possibly on an ion pair derived from it.

A similar pattern is observed with isobutoxychlorocarbene (**10**) generated photochemically from **8** (R = *i*-Bu) in MeCN. Products include isobutene (23%), 1- and 2-butenes (8−9%), *t*-BuCl (1.7%), 2-BuCl (5.8%), and *i*-BuCl (0.4%), dichloromethyl ether **12** (R = *i*-Bu, 53%), and carbene dimer (8%). Complete product distributions appear in Table 2, where the salient observations are that *i*-BuCl increases from 0.4% in MeCN to 7.3% in 5.77 M pyridine/MeCN, to 32% with 0.5 M Bu$_4$NCl/MeCN, and to 38% in Bu$_4$NCl/pyridine/MeCN. The accompanying yields of isobutene are 23, 47, 40, and 27%, respectively, under these four conditions. Again, the unrearranged "displacement" alkyl chloride fragmentation product (*i*-BuCl) becomes dominant in the chloride/pyridine/MeCN medium.

Benzyloxychlorocarbene (**2**) displays less product sensitivity. The yield of benzyl chloride, which is 83% in MeCN, increases to 91% in Bu$_4$NCl/pyr/MeCN. The balance of product, in both cases, is *N*-acetylbenzylamine, the Ritter product derived from attack of benzyl cation on MeCN.[7]

Kinetics. Absolute rate constants for the fragmentations of carbenes **9**, **10**, and **2**[7] were determined by LFP[11] by using the pyridine ylide method;[7,12] carbene **9** is illustrative. LFP at 351 nm and 24 °C of diazirine **8** (R = *n*-Bu) in MeCN ($A_{356} = 1.0$) in the presence of pyridine produced an absorption due to ylide **14** (R = *n*-Bu) at 469 nm; note that the corresponding ylide produced from MeOCCl absorbs at 472 nm.[14,15]
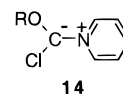
A correlation of the apparent rate constants for ylide formation, k_{obs} ($2.6-4.5 \times 10^6$ s⁻¹), vs pyridine concentration ($1.65-7.42$ M) was linear (8 points, $r = 0.992$) with a slope of 3.33×10^5 M⁻¹ s⁻¹, equivalent to the rate constant for ylide

(11) A description of our upgraded LFP system appears in the Experimental Section.

(12) (a) Jackson, J. E.; Soundararajan, N.; Platz, M. S.; Liu, M. T. H. *J. Am. Chem. Soc.* **1988**, *110*, 5595. (b) Platz, M. S.; Modarelli, D. A.; Morgan, S.; White, W. R.; Mullins, M.; Celebi, S.; Toscano, J. P. *Prog. React. Kinet.* **1994**, *19*, 93.

(13) Ylides formed from carbenes **10** and **2** were monitored at 432 and 463 nm, respectively.

(14) Ge, C.-S.; Jang, E. G.; Jefferson, E. A.; Liu, W.; Moss, R. A.; Wlostowska, J.; Xue, S. *Chem. Commun.* **1994**, 1479.

(15) Diazirines **8** in MeCN react with pyridine (but not Bu$_4$NCl) at 25 °C, affording an unknown product with $\lambda_{max} = 338$ nm. However, diazirine decay is not appreciable over the initial 30 min (HPLC). Accordingly, our diazirine−pyridine LFP experiments were performed on freshly prepared samples within 5 min of pyridine addition.

Table 2. Fragmentations of Isobutoxychlorocarbene (**10**)[a]

Medium	⟩=	⟋=	⌒⌒	⌒⌒	⟩Cl	⟍Cl	⟍⟍Cl	⟩O⌒Cl₂H	Dimer
MeCN	22.9	2.1	2.4	4.1	1.7	5.8	0.4	53.1	7.8
5.77 M pyridine	46.7	3.8	6.1	6.6	2.3	11.8	7.3	6.1	9.3
0.504 M Cl⁻[b]	39.5	2.8	3.7	3.1	2.2	8.2	31.9	5.5	3.1
5.77 M pyridine 0.504 M Cl⁻[b]	26.8	2.1	4.2	3.2	1.6	8.4	37.9	6.3	9.5

[a] All experiments in MeCN solvent at 25 °C. Values are percentages of the total products formed. [b] Cl⁻ added as *n*-Bu₄N⁺Cl⁻.
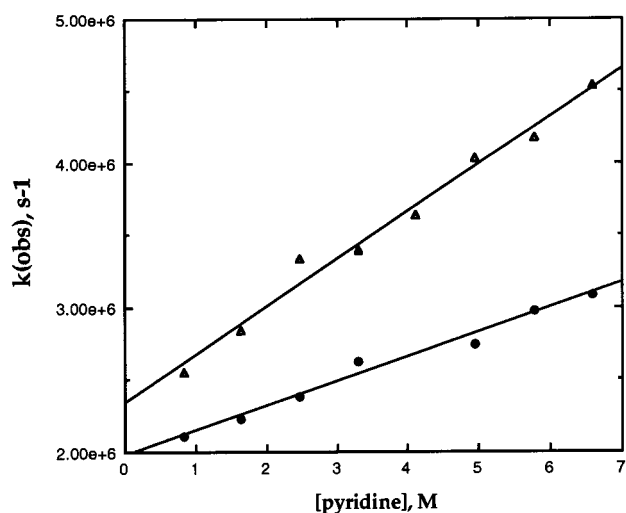
Figure 1. Representative correlations of k_{obs} for formation of ylide **14** vs [pyridine] for the fragmentations of *n*-C₄H₉OCCl (△) and *i*-C₄H₉-OCCl (●).

Figure 2. Arrhenius correlation for the fragmentation of *i*-C₄H₉OCCl (**10**); ln k_{frag} (s⁻¹) vs $1/T$ (K⁻¹).
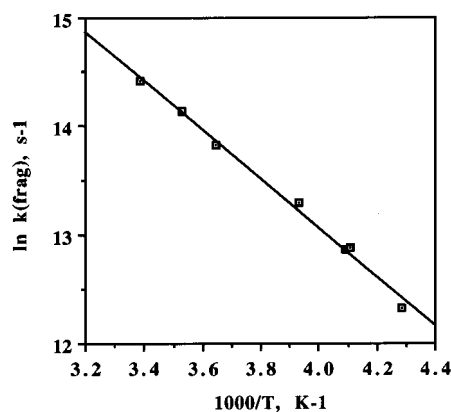
formation, k_y,[16] and a *Y* intercept of 2.1×10^6 s⁻¹; cf., Figure 1. The intercept represents the sum of rate constants for those processes that destroy carbene **9** when the concentration of pyridine is zero. At first glance, this appears to be the sum of the rate constant for fragmentation (k_{frag}) and the rate constant for the formation of dichloride **12**, which is a major product in the absence of pyridine (Table 1). However, the intercept is *extrapolated* from reactions run in the presence of pyridine. Under these conditions, HCl is scavenged, the formation of **12** is suppressed,[7] and fragmentation (Table 1) or pyridine capture become the principal modes of carbene decay. The extrapolated *Y* intercept of the correlation in Figure 1 therefore is a good estimate of k_{frag} for carbene **9**.

Repetition of these experiments afforded a second value for k_{frag} of 1.4×10^6 s⁻¹, leading to an average value of $(1.75 \pm 0.35) \times 10^6$ s⁻¹. The average rate constant for ylide formation is $k_y = (3.0 \pm 0.3) \times 10^5$ M⁻¹ s⁻¹.

In a similar manner, we determined k_{frag} for *i*-BuOCCl (**10**); cf., Figure 1. Two LFP runs afforded $k_{frag} = (1.9 \pm 0.1) \times 10^6$ s⁻¹ and $k_y = (1.7 \pm 0.06) \times 10^5$ M⁻¹ s⁻¹. We note that k_{frag} is experimentally the same for carbenes **9** and **10**. For PhCH₂-OCCl (**2**), $k_{frag} = 6.9 \times 10^5$ to 1.3×10^6 s⁻¹, depending on the data analysis.[7] These results are surprising in that the "unstabilized" primary alkyl species, **9** and **10**, appear to fragment as rapidly as the benzylic oxacarbene, **2**, which seems out of line with rate-determining fragmentation to alkyl cations, eq 2.

Arrhenius LFP studies of the fragmentation reactions of carbenes **9** and **10** were conducted over the temperature range

-40.5 to 24 °C; the quality of the data is illustrated by Figure 2 for *i*-BuOCCl (**10**).

The activation parameters were the following: (**9**) $E_a = 3.1$ kcal/mol, log $A = 8.42$ s⁻¹, $\Delta S^{\ddagger} = -21.8$ eu; and (**10**) $E_a = 4.5$ kcal/mol, log $A = 9.55$ s⁻¹, $\Delta S^{\ddagger} = -16.5$ eu. The large negative activation entropies are not in accord with naïve expectations for a fragmentation of 1 molecule to 3 products, as in eq 2, but are in the typical range for S_N1-S_N2 reactions.[17]

Chloride Dependence. The unexpectedly high k_{frag} and low $\Delta S^{\ddagger}$ values for the fragmentation of carbenes **9** and **10**, together with the striking increases in 1-BuCl and *i*-BuCl product formation elicited by added Cl⁻, suggest the intervention of bimolecular S_N2-like fragmentations, in which these carbenes (or tight ion pairs derived from them, see below) are attacked by Cl⁻ at their α carbons, eq 3.[18,19] This suggestion is strongly

$$Cl^- + RCH_2\text{-}O\text{-}\ddot{C}\text{-}Cl \longrightarrow RCH_2Cl + CO + Cl^- \quad (3)$$
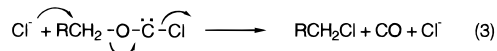
supported by additional kinetic evidence. LFP of diazirines **8** in MeCN with a constant concentration (5.77 M) of pyridine and varying quantities (0.042−0.504 M) of added Bu₄NCl give linear correlations of k_{obs} for the formation of ylides **14** as a function of [Cl⁻]; see Figure 3. The slopes of these correlations can be taken as the second-order rate constants (k_2) for quenching (i.e., fragmentation of the carbenes induced by chloride.)[12,20,21]

The linear fits in Figure 3 are quite good; the calculated standard deviations are <10% for the slopes and intercepts of the constituent correlations of k_{obs} vs [pyridine], and of k_{obs} vs

(16) Alkoxychlorocarbenes are ambiphilic and react "slowly" with pyridine.[14]

(17) See Gordon, A. J.; Ford, R. A. *The Chemist's Companion*; Wiley: New York, 1972; p 138ff.

(18) Additions of Cl⁻ at the carbenic centers of **9**, **10**, or **2** would yield RCH₂OCCl₂⁻, but these carbanions should rapidly revert to carbenes by Cl⁻ loss.[19] Note (Tables 1 and 2) that ethers **12** are suppressed, not enhanced, by added chloride.

(19) Hine, J. *Divalent Carbon*; Ronald Press: New York, 1964; p 70.
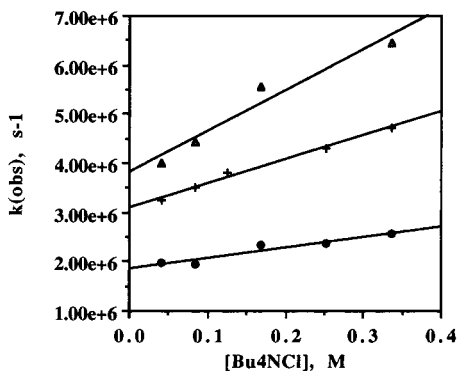
Figure 3. Examples of correlations of k_{obs} for the formation of ylides **14** (10^6 s^{-1}) from carbenes **9**, **10**, and **2** as a function of added Bu$_4$NCl (M) in 5.77 M pyridine–MeCN solutions at 24 °C: (▲) **9**, (+) **10**, and (●) **2**.

[Cl$^-$]. At [Cl$^-$] = 0, the Y intercepts of the correlations should equal k_{obs} for ylide formation at 5.77 M pyridine. This agreement is observed: for carbene **9**, the intercept is $(3.89 \pm 0.17_3) \times 10^6$ s^{-1}, whereas k_{obs}(5.77 M pyridine) = $(3.52 \pm 0.51_2) \times 10^6$ s^{-1}, while for carbene **10**, the analogous values are $(3.06 \pm 0.04_2) \times 10^6$ and $(2.86 \pm 0.12_2) \times 10^6$ s^{-1}.

The values of k_2 (M^{-1}s^{-1}) for the ROCCl/Cl$^-$ reactions (Figure 3) are $(8.2 \pm 0.2_3) \times 10^6$, $(2.7 \pm 1.4_3) \times 10^6$, and (2.2×10^6) for carbenes **9**, **10**, and **2**, in accord with expectations for the S$_N$2 mechanism depicted in eq 3. Thus, k_2 is highest for the straight-chain, primary *n*-BuOCCl, and is lowest for the benzylic PhCH$_2$OCCl, where "unimolecular" decomposition via ion pair **5**[4b] will compete with chloride attack. We should not be surprised that **9** and **10** fragment in a bimolecular fashion. Their [C≡O Cl$^-$] leaving group is isoelectronic to the [N≡N X$^-$] leaving group of the chiral α-D-substituted *n*-butyl- and isobutyldiazonium ions which decompose in water with 96% inversion, indicative of S$_N$2-like solvolysis.[22]

A referee has suggested that postulation of the S$_N$2 mechanism for **9** and **10** is not essential, and that the kinetic and product dependence on chloride concentration could also be explained by an extension of the ion pair mechanism [eq 2], in which "tight" ion pair formation is reversible, and [ROCCl] > [ion pair] with d[ion pair]/dt ∼ 0. This suggestion is formally correct, and is reminiscent of Sneen's idea that "S$_N$2" reactions of primary substrates can similarly be understood in terms of reversibly formed ion pairs and the associated rate constants for ion pair return and separation.[23]

Nevertheless, we prefer the S$_N$2 mechanism for the reactions of **9** or **10** with chloride ion. Thus, the lifetime of the benzyl cation in 50/50 trifluoroethanol/water is ∼3 × 10^{-12} s^{-1},[24] and those of *n*-butyl or isobutyl cations would be even shorter. These systems thus approach the limiting enforced concerted or "preassociation" (S$_N$2) mechanism.[25] A complication in the fragmentations of ROCCl, however, is the presence of carbon

monoxide in the gas-separated ion pairs, **5**; once formed, such ion pairs might not readily revert to the parent carbene. Differentiation of the "classical" S$_N$2 attack of Cl$^-$ on carbenes **9** and **10** from a S$_N$2-like attack of Cl$^-$ on very tight ion pairs derived from **9** or **10** is, therefore, very difficult. We are hopeful that ab intio calculations, now in progress, may shed further light on this question.[26]

The evidence is strong that carbenes **9** and **10** fragment in the presence of Cl$^-$ by an S$_N$2-like process, but what is the mechanism in the absence of added chloride? We speculate that the S$_N$2 mechanism persists, using Cl$^-$ generated during initial ROCCl → RO$^+$=C Cl$^-$ ionization[27] and, subsequently, Cl$^-$ that is liberated during alkene formation.[28]

Finally, LFP of diazirine **8** (R = PhCH$_2$) in 1,3,5-trimethoxy-benzene (TMB)−MeCN affords a [TMB]-dependent transient absorbing at 410−430 nm, consistent with the cyclohexadienyl cation formed by the trapping of the benzyl cation from the fragmentation of **2**;[29] a similar transient is not observed during an analogous experiment with *n*-butoxychlorodiazirine, suggesting that the primary butyl cation is not liberated during the fragmentation of carbene **9**, either because the fragmentation follows the S$_N$2 mechanism or because the ion pair (**5**) formed from **9** is much too tight or evanescent. Details of these experiments and of computational studies[26] will be published in due course.

Experimental Section

Solvents. Acetonitrile (Fisher, Certified A.C.S.) and pyridine (Fisher, Certified A.C.S.) were dried by reflux over CaH$_2$, followed by distillation and storage over 5A molecular sieves. Pentane (Fisher, HPLC grade) was also stored over 5A molecular sieves.

***O*-(Isobutoxy)isouronium *p*-Toluenesulfonate (11, R = *i*-C$_4$H$_9$).** This material was prepared by the method of Smith and Stevens.[3a] Anhydrous *p*-toluenesulfonic acid was obtained by heating the commercially available monohydrate (30 g, 0.16 mol) under high vacuum at 80−90 °C for 10 h. A mixture of isobutyl alcohol (18 mL, 0.2 mol), cyanamide (5.0 g, 0.12 mol), and 21 g of anhydrous *p*-TsOH in 100 mL of dry chloroform was stirred under a nitrogen atmosphere for 5 days. Precipitate isourea tosylate was filtered off, the filtrate was reduced on the rotary evaporator to ∼15 mL, and ∼ 200 mL of ether was added. The precipitate of **11** was washed with ether and dried in air to afford 21 g (0.073 mol, 61%) of **11** (R = *i*-C$_4$H$_9$), mp 92−94 °C (lit.[3a] mp 39−45 °C "indefinite"). ^{1}H NMR (200 MHz, DMSO-d_6): δ 0.95 (d, J = 6.7 Hz, 6 H, 2 Me), 1.92−2.06 (m, 1 H, CH), 2.30 (s, 3 H, Ar−CH_3), 4.03 (d, J = 6.6 Hz, 2 H, CH_2O), 7.11−7.15, 7.47−7.51 (A$_2$B$_2$, 2 H + 2 H, Ar), 8.41 (br s, 4 H, 2 NH_2).

***O*-(*n*-Butoxy)isouronium *p*-Toluenesulfonate (11, R = *n*-C$_4$H$_9$).** The above procedure was followed with 18 mL (0.20 mol) of *n*-butyl alcohol to afford 24.2 g (0.084 mol, 70%) of **11** (R = *n*-C$_4$H$_9$), mp 89−91 °C. ^{1}H NMR (as above): δ 0.93 (t, J = 7.0 Hz, 3 H, CH$_2$CH_3), 1.33−1.44 (m, 2 H, CH_2CH$_3$), 1.63−1.71 (m, 2 H, OCH$_2$CH_2), 2.31 (s, 3 H, Ar−CH_3), 4.23 (t, J = 6.4 Hz, 2 H, OCH_2), 7.11−7.15, 7.47−7.51 (A$_2$B$_2$, 2 H + 2 H, Ar), 8.40 (br s, 4 H, NH_2).

Anal. Calcd for C$_{12}$H$_{20}$N$_2$O$_4$S (288.24): C, 50.0; H, 6.99; N, 9.72. Found: C, 50.0; H, 6.75; N, 9.63.

3-Chloro-3-isobutoxydiazirine (8, R = *i*-C$_4$H$_9$).[3a] The general method of Graham was followed.[10] To 3.5 g of LiCl in DMSO was

(20) For parallel pseudo-first-order reactions, such as the reactions of ROCCl with pyridine or Cl$^-$, the rise time of any product (e.g., ylide **14**) equals the sum of the individual rate constants. Thus, at constant [pyridine], the slope of the k_{obs}(**14**) vs [Cl$^-$] correlation gives the rate constant for the reaction of ROCCl with Cl$^-$. See ref 12 for analogous cases and references.

(21) These correlations do not represent salt effects on unimolecular carbene fragmentations; there is essentially no dependence of k_{obs} on 0.05−0.5 M added Bu$_4$N$^+$BF$_4^-$.

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(27) This ionization resembles the ROSOCl → ROSO$^+$Cl$^-$ process believed to occur in "S$_N$i" reactions of primary alkylchlorosulfites: Schreiner, P. R.; Schleyer, P. v. R.; Hill, R. K. *J. Org. Chem.* **1993**, *58*, 2822.

(28) Indeed, the substantial (>40%) alkene yields attending the decompositions of **9** and **10** in pyridine/MeCN may reflect E2-like fragmentations with pyridine acting as a base.

(29) This methodology was developed by: Pezacki, J. P.; Shukla, D.; Lusztyk, J.; Warkentin, J. *J. Am. Chem. Soc.* In press. See also: Steenken, S.; Ashokkumar, M.; Maruthamuthu, P.; McClelland, R. A. *J. Am. Chem. Soc.* **1998**, *120*, 11925.

added 2.0 g (0.007 mol) of isouronium salt **11** (R = *i*-C₄H₉) and 15 mL of pentane. The mixture was cooled to 20 °C and stirred magnetically. Then, 100 mL of 12% commercial aqueous sodium hypochlorite solution ("pool chlorine") saturated with NaCl was slowly added. The reaction temperature was kept below 25 °C during the addition. After the addition was complete, stirring was continued for 15 min at 15 °C. The reaction mixture was transferred to a separatory funnel containing 150 mL of ice water, the aqueous phase was removed, and the pentane phase was washed twice with ~75 mL portions of ice water, and then dried for 2 h over CaCl₂ at 0 °C. The pentane/diazirine solution was purified by chromatography over Aldrich 200−400 mesh, 60 Å, silica gel, eluted with cold pentane. All fractions were kept at 0 °C. Pentane was reduced by rotary evaporation (behind a shield)[30] and replaced by acetonitrile. The remaining pentane was then removed by rotary evaporation at 0 °C. We thus obtained ~30 mL of an acetonitrile solution of diazirine **8** (R = *i*-C₄H₉); UV (λ_{max}) 352 (pentane), 356 nm (MeCN); A_{356} = 3.0. ¹H NMR (CDCl₃): δ 0.89 (d, *J* = 6.8 Hz, 6 H, 2 Me), 1.83−2.01 (m, 1 H, C*H*), 3.67 (d, *J* = 6.6 Hz, 2 H, C*H*₂).

3-Chloro-3-*n*-butoxydiazirine (8, R = *n*-C₄H₉). This material was prepared in the same manner as the isobutoxy analogue (above). We obtained ~30 mL of an acetonitrile solution of diazirine **8** (R = *n*-C₄H₉); UV (λ_{max}) 353 (pentane), 356 nm (MeCN); A_{356} = 3.0. ¹H NMR (CDCl₃): δ 0.88 (t, *J* = 6.8 Hz, 3 H, C*H*₃), 1.20−1.21 (m, 2 H, CH₃C*H*₂), 1.53−1.69 (m, 2 H, C*H*₂CH₂O), 3.91 (t, *J* = 6.4 Hz, 2 H, C*H*₂O).

Alternative Diazirine Preparation. The foregoing preparation[10] affords MeCN solutions of diazirine that contain traces of pentane. These solutions are adequate for LFP experiments, but the pentane interferes with GC product analysis. For product studies, we therefore used an alternative diazirine preparation adapted from Smith and Stevens.[3a]

Isouronium salts **11** (R = *i*-C₄H₉ and *n*-C₄H₉, 1 g, 0.0006 mol), lithium chloride (3.5 g), and 100 mL of DMSO were placed in a three-necked flask equipped with a dropping funnel and magnetic stirrer. The flask was connected to a train of 4 traps, the last one containing ~7 mL of dry MeCN. A glass U tube containing KOH pellets was placed between the first and second traps. The first trap attached to the reaction flask was kept between −10 and −20 °C throughout the reaction, while the second, third, and fourth traps were kept at −30, −40, and −196 (liquid N₂) °C, respectively. After the salts had been dissolved in the DMSO, sodium hypochlorite (12%) saturated with NaCl was placed in the dropping funnel, the mixture was cooled to 0 °C,

and the system was evacuated to 1−2 Torr. A shield was placed in front of the traps during the reaction.[30] The hypochlorite was then added slowly with stirring over 15 min. After the addition, stirring was continued for 10 min. At the end of the reaction, the diazirine had collected in the fourth trap. The trap was equilibrated with the atmosphere and the contents were allowed to slowly warm to room temperature. Next, the diazirine−MeCN solution was dried over CaCl₂ for 2 h. The chromatographic method was the same as described above, but dry MeCN was used as the eluent. The chromatography afforded ~25 mL of diazirine in MeCN (A_{356} = 3.0).

Photolysis of Diazirines. Solutions of diazirines **8** in MeCN (3 mL) with or without added 0.504 M Bu₄NCl or 5.77 M pyridine were photolyzed at 25 °C for 20 min with a focused Oriel lamp, λ > 320 nm (uranium glass filter). The products were analyzed by capillary GC and by GC-MS. For the *i*-BuOCCl products, we used a 30 m × 0.25 mm (o.d.) × 0.25 μm (i.d.) HPInnowax (cross-linked poly(ethylene glycol)) column at 25 °C (3 min), programmed to 200 °C at 30 deg/min. For low boiling products, we used a SPB-20 (20% diphenyl, 80% dimethylsiloxane) column at −15 °C (4 min), programmed to 200 °C at 30 deg/min. For the *n*-BuOCCl products, we employed a CPSil-5CB (poly(dimethylsiloxane)) column at 25 °C (3 min), programmed to 200 °C at 30 deg/min. Lower boiling products were analyzed as above. For the products of PhCH₂OCCl, we used the Innowax column (see above) at 150 °C, programmed to 200 °C at 30 deg/min. Products are described above; see Tables 1 and 2 and text. Product identities were confirmed by GC and GC-MS comparisons to authentic samples (Aldrich), while dichloride **12** and azine **13** were identified by GC-MS.

Laser Flash Photolysis. These experiments were performed with a Lambda Physik COMPex model 120 excimer laser using a Spectra Gases fill of 0.1875% F₂, 0.468% Xe, and 99.334% Ne. The laser emitted 10 ns pulses at 351 nm and 80 mJ. The detection unit comprised a 1000 W Oriel xenon arc lamp, a 1 in. Uniblitz shutter, Instruments SA grating monochromator, and a RCA 4840 photomultiplier tube wired in a 5-dynode configuration. The data collection and analysis system included a Stanford Research Systems model DG535 4-channel digital delay/pulse generator and a Tektronix TDS 320 2-channel oscilloscope. Data analysis used the Igor Pro 2.00 program (Wave Metrics, Inc.).

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(30) All diazirine preparations were carried out behind shields. No explosions were encountered, but these compounds are explosive, and *neat* diazirines must be avoided.