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Fragmentation of Menthyl- and Neomenthyloxychlorocarbenes: Elimination and Substitution Reactions of Alicyclic Oxychlorocarbenes

Robert A. Moss,* Lauren A. Johnson, Monica Kacprzynski, and Ronald R. Sauers

Department of Chemistry and Chemical Biology, Rutgers, The State University of New Jersey, New Brunswick, New Jersey 08903

moss@rutchem.rutgers.edu

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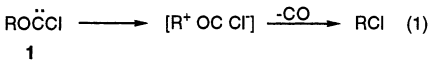
Fragmentations of menthyloxychlorocarbene (**5**) and neomenthyloxychlorocarbene (**6**) follow distinct pathways to (largely) stereochemically retained substitution products from **5** and elimination products from **6**, closely resembling the product distributions from deaminations of the corresponding menthyl- and neomenthylamines.

Introduction

The fragmentation of alkoxychlorocarbenes (**1**) constitutes an intersection of carbene, carbocation, elimination, and substitution chemistry.[1] In polar solvents, the fragmentations proceed through tight, short-lived ion pairs; eq 1.[1−3] When R is chiral, RCl is formed by anion return



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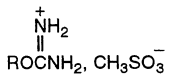
with substantial but incomplete stereochemical retention, e.g., for R = PhCHD, 60−80% net retention in MeCN,[4] and for R = 2-butyl, 56% net retention in MeCN.[5] When loss of a β-proton is feasible, net elimination of HCl produces alkenes, in addition to RCl, e.g., in the fragmentations of *exo*- and *endo*-2-norbornyloxychlorocarbenes.[6]

Alicyclic systems are well suited to a simultaneous study of the stereoselectivity of fragmentation-initiated substitution reactions, coupled with an evaluation of the competing elimination reactions. Here, we report instructive results from the fragmentations of cyclohexyl-, menthyl-, and neomenthyloxychlorocarbenes.

Results and Discussion

Cyclohexanol, menthol, and neomenthol were each converted to the corresponding isouronium methanesulfonate salts, **2**, with cyanamide and methanesulfonic acid in THF.[7] Graham oxidation[8] of **2** with 12% aqueous NaOCl furnished alkoxychlorodiazirines **3**, which were purified by column chromatography (silica gel, pentane) and characterized by NMR and UV spectroscopy.[9]



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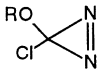

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Photolysis of **3** (R = cyclohexyl) in MeCN or 1,2-dichloroethane (DCE) afforded cyclohexyloxychlorocarbene (**4**) and thence cyclohexyl chloride (62 or 70%) and cyclohexene (32 or 30%),[10,11] representing the fragmentation of **4**, followed either by the collapse of the ion pair or loss of HCl; eq 2.

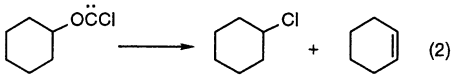

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Table 1 summarizes the product distributions from **4** in DCE. Experiments were also conducted with added pyridine to mimic our laser flash photolytic kinetics experiments (see below) and with added chloride ion (0.504 M tetrabutylammonium chloride) to determine if

TABLE 1. Product Distributions from Cyclohexyloxychlorocarbene (4)[a]

additive	cyclohexyl chloride	cyclohexene
none	69.7	30.3
5.77 M pyridine	73.6	25.4
0.504 M Cl^-	67.4	32.6
0.504 M Cl^- and 5.77 M pyr	73.3	26.7

[a] In DCE at 25 °C; distributions in percent.

(1) Moss, R. A. *Acc. Chem. Res.* **1999**, *32*, 969.
(2) Moss, R. A.; Ma, Y.; Zeng, F.; Sauers, R. R.; Bally, T.; Maltsev, A.; Toscano, J. P.; Showalter, B. M. *J. Phys. Chem. A.* **2002**, *106*, 12280.
(3) Moss, R. A.; Zeng, F.; Fedé, J.-M.; Sauers, R. R. *Org. Lett.* **2002**, *4*, 2341.
(4) Moss, R. A.; Kim, H. R. *Tetrahedron Lett.* **1990**, *31*, 4715.
(5) Moss, R. A.; Balcerzak, P. *J. Am. Chem. Soc.* **1992**, *114*, 9386.
(6) Moss, R. A.; Zeng, F.; Sauers, R. R.; Toscano, J. P. *J. Am. Chem. Soc.* **2001**, *123*, 8109.
(7) Moss, R. A.; Kaczmarczyk, G. M.; Johnson, L. A. *Synth. Commun.* **2000**, *30*, 3233.
(8) Graham, W. H. *J. Am. Chem. Soc.* **1965**, *87*, 4396.
(9) λ_{max} (nm) for all three diazirines: 354 (pentane), 356 (MeCN), 359 (dichloroethane).
(10) All products were identified by capillary GC spiking experiments with authentic materials and by GC−MS.
(11) In MeCN, 6% of *N*-cyclohexylacetamide (Ritter product) was formed by carbene attack on the solvent, followed by hydrolysis by traces of water.

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TABLE 2. Product Distributions (%) from Menthyloxychlorocarbene (5)[a]

solvent	additive	7	8	9	10	menthyl formate[b]
DCE[c]		59.0	16.5	11.1	2.4	2.6
DCE[d]	TBAC[e]	46.9	16.3	24.5	4.9	1.7
MeCN[f]		56.0	25.7	8.1	2.7	3.1
MeCN[g]	TBAC[e]	40.1	11.1	24.2	4.0	5.7
1,4-Dioxane[h]		54.9	15.9	14.1	2.8	tr

[a] At 25 °C. [b] See ref 13. [c] Four unknown products totaling 8.4% were formed. [d] Four unknown products totaling 5.7% were also formed. [e] 2.52 M tetrabutylammonium chloride. [f] Three unknown products totaling 4.4% were also formed. [g] Three unknown products totaling 14.9% were also formed. [h] Five unknown products totaling 12.3% were also formed.

TABLE 3. Product Distributions (%) from Neomenthyloxychlorocarbene (6)[a]

solvent	additive	7	8	9	10	neomenthyl formate[b]
DCE[c]		2.9	7.8	58.7	16.2	5.4
DCE[d]	TBAC[e]	2.3	1.5	69.5	21.6	
MeCN[f]		tr	6.9	61.5	13.7	9.4
MeCN[g]	TBAC[e]	1.8	1.5	73.3	20.0	
1,4-dioxane[h]		tr	15.5	51.1	20.0	1.0

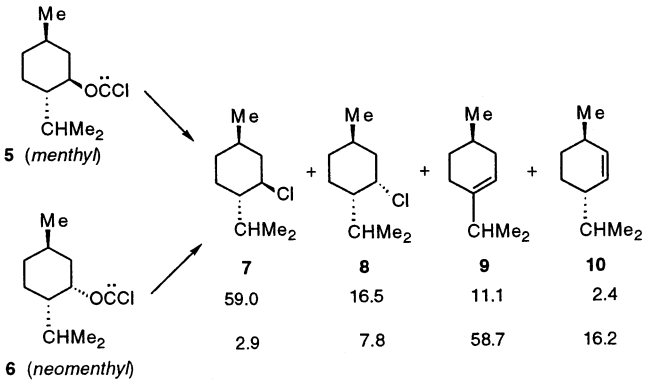
[a] 25 °C. [b] See ref 13. [c] Three unknown products totaling 9.0% were also formed. [d] Two unknown products totaling 5.1% were also formed. [e] 2.52 M tetrabutylammonium chloride. [f] Two unknown products totaling 8.5% were also formed. [g] One unknown product (3.4%) was present. [h] Four unknown products totaling 12.3% were also formed.

chloride-induced S_N2 fragmentation[12] of carbene **4** was an important process. Cyclohexyl chloride increases very slightly in the presence of 5.77 M pyridine, but not in the presence of chloride ion. There is no evidence for an S_N2 component to the fragmentation of **4**, which, we conclude, follows the unimolecular pathway of eq 1, with ion pair return to cyclohexyl chloride somewhat more than twice as efficient as HCl elimination to cyclohexene.

We next examined the fragmentations of the conformationally "locked" menthyl- (**5**) and neomenthyloxychlorocarbene (**6**), generated by the photolysis ($\lambda \sim 350$ nm) of the appropriate diazirines (**3**) in MeCN, DCE, or 1,4-dioxane. The products[10,13] and their distributions from **5** are shown in Table 2, while those from carbene **6** appear in Table 3. Scheme 1 illustrates the products, together with the representative DCE distributions.

From the fragmentation of menthyloxychlorocarbene (**5**), where the carbene moiety is equatorial (**5′**), we obtain 59% of the return (substitution) product, menthyl chloride (**7**), formed with retention, along with 16.5% of the inverted return product, neomenthyl chloride (**8**); see Table 2. The **7**/**8** distribution corresponds to 56% net retention in the return process. There is also 13.5% of elimination, with the expected dominance of the more highly substituted 3-menthene (**9**, 11.1%) over 2-menthene (**10**, 2.4%). Note that 3-menthene formation here constitutes "cis" elimination. The overall ratio of substitution (return) to elimination is 5.6.

SCHEME 1[a]

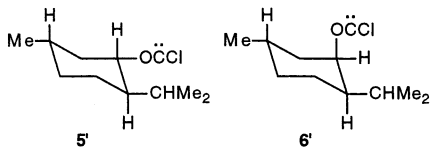


[a] Product distributions are in percent, as determined by GC;[10,13] the menthyl-OCCl (**5**) distribution appears first.

Similar overall patterns are found in MeCN and dioxane solvents. In MeCN, **7**/**8** is 56.0/25.7, corresponding to 37% net retention in chloride return, somewhat less than the 56% net retention observed in DCE. This may be due to the greater polarity of MeCN (dielectric constant of 36.6 at 20 °C) relative to DCE (dielectric constant, 10.4), with attendant greater loss of stereochemical "memory" in a longer lived ion pair in the more polar solvent. In dioxane (dielectric constant 2.2), the stereochemical result is 55% net retention, very similar to the outcome in DCE. The dominance of 3-menthene (**9**) over 2-menthene (**10**) persists in all three solvents, and the overall ratio of substitution (return) to elimination is 7.6 in MeCN and 4.2 in dioxane, compared to 5.6 in DCE.

The effect of added chloride ion in DCE or MeCN is mainly to increase elimination, especially to 3-menthene, at the expense of the substitution products. The chloride functions mainly as a base to accept H^+, rather than as a nucleophile to afford substitution product **8**, by S_N2 attack[12] on carbene **5**. As a base, the added chloride ion can divert the ion pair toward alkene by accepting a β-proton. The tertiary axial proton at C-4, removal of which leads to the more highly substituted alkene isomer (3-menthene), is a particularly attractive target.

In contrast, neomenthyloxychlorocarbene (**6**), with an axial carbene moiety (**6′**), affords mainly elimination products **9** (58.7%) and **10** (16.2%) in DCE, distantly followed by chloride return products **8** (7.8%) and **7** (2.9%); see Table 3. The return products are again formed with net retention (46%), but the striking difference between the fragmentations of **6** and **5** is the dominance of elimination pathways in the former case. For carbene **6**, substitution/elimination = 0.14, whereas this ratio is 5.6 for carbene **5**.

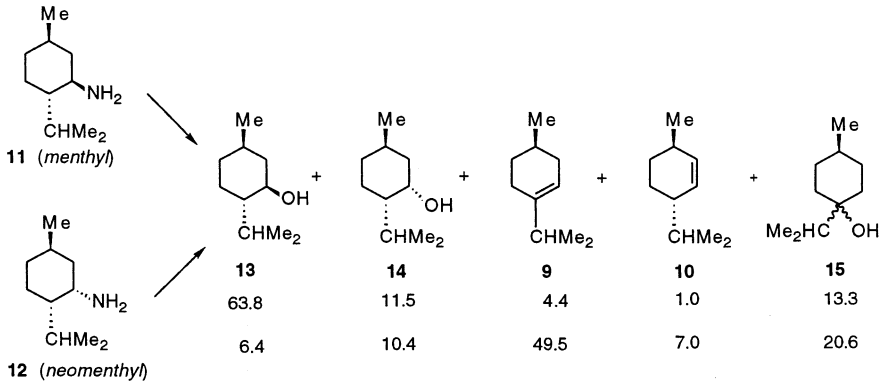


Again, these trends are maintained in MeCN and dioxane solvents, with minor variations, and as with carbene **5**, addition of chloride ions in DCE or MeCN solvents leads to enhanced elimination, rather than to an increase of inverting substitution.

(12) Moss, R. A.; Johnson, L. A.; Merrer, D. C.; Lee, G. E., Jr. *J. Am. Chem. Soc.* **1999**, *121*, 5940.

(13) In addition to the fragmentation products shown in Scheme 1, 1−10% of menthyl formate (from **5**) and neomenthyl formate (from **6**) were formed through trapping of the carbenes by adventitious water. The formates were identified by GC and GC−MS comparisons with authentic materials prepared from menthol or neomenthol.

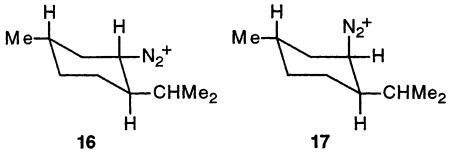
SCHEME 2[a]



[a] Deamination of menthyl- and neomenthylamine with $NaNO_2$, HOAc, and H_2O at 60 °C; cf. ref 16. Product distributions are in percent, as determined by GC;[10,13] the menthylamine (**11**) distribution appears first.

We have previously noted the parallel between carbene fragmentation, in which CO is lost, and deaminative processes in which N_2 is the leaving group.[1,14] This analogy was first proposed by Skell and Starer,[15] but not until the present instance has it been subjected to really detailed stereochemical and substitution/elimination scrutiny. For comparison to Scheme 1, deaminations of menthylamine (**11**) and neomenthylamine (**12**) with aqueous nitrous and acetic acids provide the substitution (**13**, **14**), elimination (**9**, **10**), and hydride-shift (**15**) products illustrated in Scheme 2.[16]

The deamination product distributions of Feltkamp[16] are remarkably similar to those of the corresponding carbene fragmentations (Scheme 1). From menthylamine, where nitrous acid deamination proceeds via equatorial diazonium ion **16**, one obtains 63.8% of substitution (solvolysis) product menthol (**13**), formed with retention, accompanied by 11.5% of inverted solvolysis product neomenthol (**14**). There is 69% net retention in the solvolysis of **16**, compared to 56% net retention in the fragmentation of carbene **5′** (see above). Elimination (5.4%) is a minor process, with 3-menthene (**9**) the dominant olefin. The substitution/elimination ratio is 13.9.

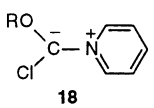


From neomenthylamine (**12**), one obtains via axial diazonium ion **17**, 56.5% of 3-menthene and 2-menthene in a distribution of ~ 7.1:1, accompanied by solvolysis products **14** (10.4%) and **13** (6.4%). Again, solvolysis proceeds with net retention (24%). As with carbene fragmentation, elimination is dominant for the neomenthyl substrate: in the deamination of **12**, elimination/substitution ~ 3.4.

The axial leaving group → elimination, equatorial leaving group → substitution pattern is paradigmatic for the decomposition of alicyclic diazonium ions; similar observations extend to the deaminations of *cis*- and *trans*-4-*tert*-butylcyclohexylamine.[17] Indeed, the fragmentations of *cis*- and *trans*-4-methylcyclohexyloxychlorocarbenes follow a similar pattern.[18]

Clearly, deaminations of **11** and **12** do not pass through equilibrated 3-menthyl cations; the product manifolds remain distinct. Diazonium ions **16** and **17** may be paired with anions, possibly H-bonded to water molecules, thus leading to net retention in substitution processes.[17] When the diazonium leaving group is axial, loss of a β axial proton (to an anion or water) is stereoelectronically facilitated, and elimination dominates. For the fragmentations of **5** and **6**, short-lived ion pairs provide analogous product-forming pathways. These ion pairs do not equilibrate within their short lifetimes; "memory" of their origin persists. The very close analogies between the menthyl and neomenthyl product distributions for the fragmentations of alkyldiazonium ions **16** and **17** and alkoxychlorocarbenes **5′** and **6′** supports the contention that the carbene fragmentations, like the diazonium ion decompositions,[17] are ionic.

We also measured absolute rate constants for the fragmentations of cyclohexyloxychlorocarbene (**4**) and carbenes **5** and **6** by laser flash photolysis (LFP)[12,19] of diazirines **3** at 351 nm using UV detection and pyridine ylide visualization.[20] Thus, LFP at 351 nm and 25 °C in DCE of diazirine precursors **3** ($A_{350} = 1.0$) in the presence of pyridine produced absorptions at 430−432 nm due to the formation of ylides **18**. Correlations of the apparent rate constants for ylide formation vs pyridine concentration were linear, with slopes representing the rate constants for ylide formation (k_y) and *Y*-intercepts representing the rate constants for carbene fragmentation, k_{frag}.[19,20] The rate constants are collected in Table 4.



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These rate constants are "normal" for *sec*-alkyloxychlorocarbenes. For example, k_{frag} for cyclopentyloxychlorocarbene in DCE is 8.7×10^4 s^{-1}.[6] We do note that k_{frag}

(14) Moss, RA.; Ma, Y. *Tetrahedron Lett.* **2001**, *42*, 6045.
(15) Skell, P. S.; Starer, I. *J. Am. Chem. Soc.* **1959**, *81*, 4117.
(16) Feltkamp, H.; Koch, F.; Thanh, T. N. *Annalen* **1967**, *707*, 95.
(17) See the discussion in Zollinger, H. *Diazo Chemistry II*; VCH Publishers: New York, 1995; p 278ff and references therein.

TABLE 4. Rate Constants for Carbene Fragmentation[a]

carbene	k_{frag} (s^{-1})	k_y ($M^{-1}s^{-1}$)
4	$3.3 \pm (0.02) \times 10^4$	$3.0 \pm (0.4) \times 10^4$
5	$6.1 \pm (0.4) \times 10^4$	$7.5 \pm (0.7) \times 10^3$
6	$1.2 \pm (0.06) \times 10^5$	$4.3 \pm (0.3) \times 10^4$

[a] At 25 °C in DCE. Errors are average deviations of two experiments.

for **6** (axial carbene) is about twice that of **5** (equatorial carbene).

Conclusion

The fragmentations of menthyloxychlorocarbene (**5**) and neomenthyloxychlorocarbene (**6**) follow distinct pathways to (largely) stereochemically retained substitution products from **5** and elimination products from **6**, closely resembling the product distributions from deaminations of the corresponding menthyl- and neomenthylamines. These carbene fragmentations, like the decompositions of the alkyldiazonium ion intermediates of the amine deaminations, are readily understood in terms of short-lived ion pair intermediates in polar solvents.

Experimental Section

General Methods. Melting points are uncorrected. Proton NMR spectra were determined at 200, 300, or 400 MHz. ^{13}C NMR spectra were measured at 75 or 100 MHz. Chemical shifts are reported in ppm (δ) relative to TMS. GC−MS data were obtained using a 5% phenyldimethylpolysiloxane column attached to a mass selective detector. Photolyses were conducted with a photochemical reactor equipped with RPR-3500 bulbs ($\lambda = 350$ nm) or with a UV lamp with a uranium glass filter ($\lambda > 330$ nm). UV spectra were determined on a diode array spectrophotometer.

Acetonitrile and pyridine were dried by distillation from CaH_2 and stored over molecular sieves. 1,4-Dioxane was dried over KOH and distilled from sodium benzophenone under N_2 prior to use. All other chemicals were used as received.

LFP experiments utilized a Lambda Physik COMPex 120 XeF excimer laser. The xenon fluoride laser produced pulses at 351 nm with 14-ns durations and an average power of 35−50 mJ/pulse. The laser beam was focused by a plano-convex lens to irradiate the sample cell at a 90° angle to the monitoring beam. The detection light source was an Oriel 1000-W HG(Xe) arc lamp; exposure of the sample to the lamp was controlled by a fast, 1-in. Uniblitz shutter. Light was transmitted through the sample into an ISA H-10 grating monochromator, followed by an RCA 4840 photomultiplier tube (PMT) wired in a five dynode configuration. The output of the PMT was transmitted to a Tektronix TDS 520A or 320 two channel oscilloscope. The sequencing of the experiments was controlled by a Stanford Research Systems DG535 four channel digital delay/pulse generator. Data were processed with Igor Pro 2.0 software (Wavemetrics, Inc.) on a Macintosh IIsi computer. Suprasil quartz cuvettes (1 × 1 cm) were used to hold the samples.

Preparation of 3-Chloro-3-cyclohexyloxydiazirine. Cyclohexyl Isouronium Methanesulfonate.[7] Into a 100 mL round-bottom flask fitted with a $CaCl_2$ drying tube and magnetic stirring bar were placed 2.0 g (47.6 mmol) of cyanamide and 57.0 g (0.57 mol) of cyclohexanol. To this solution was added 4.6 g (47.6 mmol) of methanesulfonic acid. The reaction mixture was stirred at room temperature for 24 h. The mixture was then diluted with 300 mL of ether, whereupon a white precipitate formed. This solid was filtered, washed with 3 × 50 mL of ether, and then dried under high vacuum at room temperature, affording 10.6 g (44.9 mmol, 95%) of **2** (R = cyclohexyl). Mp: 77−79 °C. ^1H NMR (200 MHz, DMSO-d_6): δ 1.22−1.95 (m, 10H), 2.39 (s, 3H), 4.60−4.72 (br m, 1H), 8.46 (br s, 4H). ^{13}C NMR (100 MHz, DMSO-d_6): δ 22.7, 24.3, 38.9, 39.7, 78.9, 160.7.

Anal. Calcd for $C_8H_{18}N_2O_4S \cdot 0.4\ H_2O$: C, 39.1; H, 7.7; N, 11.4 Found: C, 38.7; H, 7.3; N, 11.8. (The solid salt was hygroscopic.)

3-Chloro-3-cyclohexyloxydiazirine.[8] Into a three-neck round-bottom flask fitted with a dropping funnel, magnetic stirring bar, and a thermometer were placed 4 g of LiCl, 2.0 g of the isouronium salt, 100 mL of DMSO, and 50 mL of pentane. Aqueous NaOCl solution (200 mL; "pool chlorine", 12.5% $^-$OCl) was saturated with NaCl and added to the reaction solution with stirring, maintaining the temperature below 30 °C. After this addition, stirring was continued for another 15 min at room temperature. The reaction solution was poured into a separatory funnel containing 200 mL of ice−water, and the pentane layer was separated, washed with ice−water (2 × 200 mL), and dried over $CaCl_2$. The pentane solution was passed through a silica gel column (pentane eluent), affording diazirine **3** (R = cyclohexyl). We obtained MeCN or DCE solutions of the diazirine: UV λ_{max} 352 nm (pentane), 356 nm (MeCN), 359 nm (DCE); $A_{356} = 1.0$. ^1H NMR (400 MHz, CD_3CN): δ 1.20−2.10 (m, 10 H), 4.10−4.20 (m, 1H). ^{13}C NMR (100 MHz, DMSO-d_6): δ 23.3, 25.2, 31.9, 70.2, 77.9.

Preparation of 3-Chloro-3-menthyloxydiazirine. 3-Menthylisouronium Methanesulfonate and Triflate. Into a 100 mL round-bottom flask fitted with a $CaCl_2$ drying tube and magnetic stirring bar were placed 22.3 g (0.143 mol) of menthol, 2.0 g (47.6 mmol) of cyanamide, and 20 mL of anhydrous THF. To this solution was slowly added 4.21 mL (47.6 mmol) of CH_3SO_3H. The mixture was stirred at room temperature for 24 h, and then 300 mL of ether was added. Upon addition of the ether, an oil formed at the bottom of the flask. This oil was washed twice with 100 mL of ether, and then the residual ether was removed by rotary evaporation giving isouronium salt **2** (R-3-menthyl) as an oil. Although this oil was used in most experiments, it was difficult to obtain as a completely pure compound suitable for elemental analysis.

A similar salt was prepared with the triflate counterion, $CF_3SO_3^-$. Both salts react to form the same diazirine through Graham oxidation. The triflate salt was prepared in exactly the same manner as the mesylate salt, but CF_3SO_3H (7.14 g, 47.6 mmol) was used instead of CH_3SO_3H. After 24 h, the reaction mixture was diluted with 300 mL of pentane and an oil formed. This oil was washed with 2 × 100 mL of pentane. The residual pentane was then removed by rotary evaporation, and then 100 mL of chloroform was added. The solid precipitate was filtered off and discarded, and the chloroform was removed by rotary evaporation from the filtrate. The isouronium salt (orange oil) which remained was formed in 43% yield (7.08 g, 20.5 mmol). ^1H NMR (300 MHz, DMSO-d_6): δ 0.90, 0.88, and 0.76 (3 H, each d, J = 6.8, 7.2, and 6.8 Hz, respectively), 0.70−2.10 (m, 9H), 4.50 (m, 1 H), 8.4 (br m, 4 H). ^{13}C NMR (75 MHz, DMSO-d_6): δ 15.9, 20.0, 21.4, 22.6, 25.6, 30.2, 32.9, 39.4, 46.5, 80.6, 120.3, 160.5.

Anal. Calcd for $C_{12}H_{23}N_2O_4SF_3$: C, 41.37; H, 6.65; N, 8.04. Found: C, 41.13; H, 6.66; N, 7.83.

3-Chloro-3-(3-menthyloxy)diazirine.[8] This material was prepared from the foregoing isouronium salt by Graham oxidation[8] in the same manner as 3-chloro-3-cyclohexyloxydi-

(18) From *trans*-4-methylcyclohexyloxychlorocarbene (*e*,*e*) we obtain *trans*-4-methylcyclohexyl chloride (59%), *cis*-4-methylcyclohexyl chloride (17%), and 4-methylcyclohexene (16%). From the cis carbene (*ae*,*ea*), these products are formed in yields of 32, 8, and 47%, respectively. Johnson, L. A. Ph.D. Dissertation, Rutgers University, 2001.

(19) Moss, R. A.; Ge, C.-S.; Maksimovic, L. *J. Am. Chem. Soc.* **1996**, *118*, 9792. Moss, R. A.; Johnson, L. A.; Yan, S.; Toscano, J. P.; Showalter, B. M. *J. Am. Chem. Soc.* **2000**, *122*, 11256.

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azirine (see above). The diazirine (**3**, R = 3-menthyloxy) had UV (λ_{max}) 354 nm (pentane), 356 mn (MeCN), 359 nm (DCE), 356 nm (1,4-dioxane); $A_{356} = 1.0$. ^{1}H NMR (200 MHz, $CDCl_3$): δ 0.75−2.40 (m, 9H), 0.77 (d, J = 6 Hz, 3H), 0.86, 0.96 (2 d, J = 6 Hz, 6 H), 3.90−4.05 (m, J = 4 Hz, 1H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 15.7, 20.7, 22.1, 23.0, 25.4, 31.5, 34.0, 41.2, 47.1, 70.4, 80.0.

Preparation of 3-Chloro-3-neomenthyloxydiazirine. 3-Neomenthylisouronium Triflate. Into a 100 mL round-bottom flask fitted with a $CaCl_2$ drying tube and magnetic stirring bar were placed 22.3 g (0.143 mol) of neomenthol, 2.0 g (47.6 mmol) of cyanamide, and 20 mL of anhydrous THF. To this solution was slowly added 7.14 mL (47.6 mmol) of CF_3SO_3H. The mixture was stirred at room temperature for 24 h, and then 300 mL of pentane was added. Upon addition of the pentane, an oil formed at the bottom of the flask. This oil was washed twice with 100 mL of pentane, and residual pentane was then removed by rotary evaporation leaving a mixture of the desired neomenthyl isouronium salt and a byproduct, isouronium trifluoromethanesulfonate, in a ratio of 0.2/1 as determined by ^{1}H NMR. (When more isouronium trifluoromethanesulfonate was added to this mixture, the NMR peak for the byproduct increased.) Many unsuccessful attempts were made to separate the byproduct. However, it is lost during Graham oxidation to the diazirine, and the NMR spectra of the latter are free of impurities (see below).

^{1}H NMR (400 MHz, DMSO-d_6) for **3** (R = 3-neomenthyl): δ 0.74, 0.82, and 0.86 (3 d, J = 6.4, 6.4, and 7.2 Hz, respectively, 9H), 0.70−2.10 (m, 9H), 4.48 (m, 1H), 8.3 (br m, 4H). ^{13}C NMR (100 MHz, DMSO-d_6): δ 16.3, 20.4, 21.7, 23.0, 26.0, 30.6, 33.3, 39.8, 46.9, 81.1, 120.9, 161.2.

3-Chloro-3-(3-neomenthyloxy)diazirine.[8] This material was prepared from the foregoing isouronium salt by Graham oxidation[8] in the same manner as 3-chloro-3-cyclohexyloxydiazirine (see above). Diazirine **3** (R = 3-neomenthyl) had UV (λ_{max}) 354 nm (pentane), 356 nm (MeCN), 359 nm (DCE), 356 nm (1,4-dioxane); $A_{356} = 1.0$. ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.64, 0.92, 1.02, (3 d, J = 6.4, 6.8, and 7.2 Hz, respectively, 9H), 0.75−2.44 (m, 9H), 4.03 (m, 1 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 15.8, 20.7, 22.1, 23.0, 25.4, 31.6, 34.0, 41.2, 47.1, 70.4, 80.4.

Product Studies. From carbene **4**, products were analyzed by capillary GC and GC−MS. A CPSil-5CB (poly(dimethylsiloxane)) GC column was utilized. Products included cyclohexene, cyclohexyl chloride, and *N*-cyclohexylacetamide.[11] The identity of cyclohexene was confirmed by a GC spiking experiment with an authentic sample. GC−MS: *m/e* 82 (base peak, M^+).The identity of cyclohexyl chloride was confirmed by a GC spiking experiment with an authentic sample. GC−MS: *m/e* 118/120 ($M^+/M^+ + 2$), 83 (base peak, $M^+ - 35$). The identity of *N*-cyclohexylacetamide was confirmed by a GC spiking experiment with an authentic sample.[21] GC−MS: *m/e* 141 (M^+), 83 (base peak, $M^+ - 58$).

From carbenes **5** and **6**, products were analyzed by capillary GC using a HP-5 Trace (5% Ph Me Siloxane) column: The identity of 2-menthene (**10**) was confirmed by a GC-spiking experiment with an authentic sample. The identity of 3-menthene (**9**) was confirmed by a GC spiking experiment with an authentic sample and by NMR comparison to the literature spectrum.[22] The identity of menthyl chloride (**7**) was confirmed by a GC-spiking experiment with an authentic sample and by NMR comparison to the literature spectrum.[23] Neomenthyl chloride (**8**) was prepared from neomenthol, thionyl chloride and pyridine (reflux, 2 h), purified by chromatography, and identified by comparison of its ^{1}H NMR spectrum with the literature spectrum.[23] The product **8** formed from carbenes **5** or **6** was identified by a GC-spiking experiment with the authentic material and by NMR analysis of product mixtures.

LFP Studies. Solutions of diazirines **3** in DCE ($A_{356} = 1.0$) containing 1.65−8.25 M pyridine (1.5 mL total solution) were irradiated with an XeF excimer laser at 351 nm at 25 °C. Further description of the methodology and the observed rate constants (Table 4) can be found in the Results and Discussion.

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