protonated species can be controlled by the pK_a of the proton donor, changing the solvent polarity, or by varying the temperature. Unlike Schiff bases, ground-state polyene aldehydes do not readily accept protons from alcohol donors. Excited aldehydes, on the other hand, can compete for protons, at least at low temperature.

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Registry No. (*E*)-Crotonaldehyde, 123-73-9; *all-trans*-2,4,6,8-decatetraenal, 39806-05-8.

Reactions of Dimethoxycarbene and Fluoromethoxycarbene with Hydroxyl Compounds. Absolute Rate Constants and the Heat of Formation of Dimethoxycarbene

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Abstract: Dimethoxycarbene [$(MeO)_2C$] and fluoromethoxycarbene (FCOMe) were photochemically generated from the appropriate diazirines (**2a** and **2b**) and characterized by UV and IR spectroscopy in cold matrices and by UV in solution at 20–25 °C. Laser flash photolytic studies determined rate constants for the reactions of the carbenes with ethanol, methanol, chloroethanol, fluoroethanol, trifluoroethanol, hexafluoroisopropyl alcohol, and acetic acid. The reactivity of $(MeO)_2C$ with the alcohols spanned 4 orders of magnitude, with k_ψ for carbene decay in 1 M ROH/CH_3CN ranging from 3.2×10^4 s^{-1} (ethanol) to 6.7×10^8 s^{-1} (hexafluoroisopropyl alcohol). A Brønsted correlation ($\alpha = -0.66$) was obtained between log k_ψ for the decay of $(MeO)_2C$ in 1 M ROH/CH_3CN and the pK_a of ROH (in water). FCOMe was much less reactive toward ROH than $(MeO)_2C$; only with hexafluoroisopropyl alcohol ($k_\psi \sim 9 \times 10^3$ s^{-1} for carbene decay in 1 M ROH/CH_3CN) could quenching be observed. Products of some of the carbene/alcohol reactions were characterized. A photoacoustic calorimetry study of the $(MeO)_2$/MeOH reaction afforded $\Delta H_f \sim -61$ kcal/mol for $(MeO)_2C$; ΔH_f for FCOMe was estimated at ~ -53 to -56 kcal/mol. The mechanism(s) of the carbene/O–H insertion reactions are discussed. The results of ab initio and semiempirical molecular orbital calculations on FCOMe are presented.

The reaction of carbenes with hydroxylic substrates have long been studied by classical, product-based methods.[2] In the case of *singlet* carbenes, several mechanisms have been considered for the archetypal O–H "insertion" reaction: (a) electrophilic attack on an oxygen lone pair with the (possibly reversible) formation of an ylide that subsequently suffers O to C proton transfer; (b) *direct*, three-center O–H insertion; or (c) carbene protonation, followed by rapid collapse of the resulting carbocation/oxide ion pair.[2] Conventional wisdom dictates that a nucleophilic carbene, where the reactivity is dominated by the lone electron pair, ought to adhere to mechanisms (c) or possibly (b), whereas an electrophilic carbene, with reactivity centered in its vacant p orbital, should prefer mechanisms (a) or (b).

The advent of laser flash photolytic (LFP) methods,[3] and appropriate carbene precursors,[4] has now made it possible to obtain absolute kinetic data for many carbene reactions,[5-7] including those with hydroxyl compounds. The reactions of singlet carbenes with O–H bonds can now be directly monitored,[8] so that the mechanistic trichotomy can be subjected to renewed scrutiny. Indeed, we recently reported that the O–H insertion of nucleophilic[6] dimethoxycarbene into MeOH(D) was attended by a primary kinetic isotope effect of 3.3 ± 0.5, suggestive of substantial O–H to carbene proton transfer during the reaction.[9] Moreover, application of time-resolved photoacoustic calorimetry (PAC) to the carbene/O–H reaction provides experimental data from which one can estimate the heat of formation of the carbene.[10]

In this report, we apply both LFP and PAC to the reaction dynamics of dimethoxycarbene, $(MeO)_2C$, and fluoromethoxycarbene, FCOMe, with alcohols. The results that we obtain lead to a Brønsted correlation between the absolute rate constants of the $(MeO)_2C$/O–H reactions and the (aqueous) pK_a values of the OH moieties as well as a value of ~ -61 kcal/mol for the heat of formation of $(MeO)_2C$.

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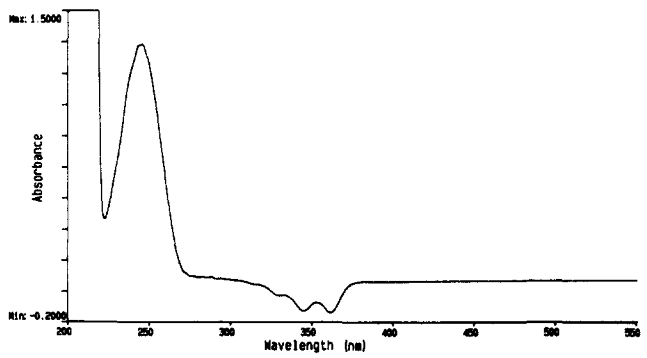
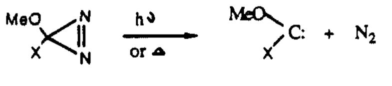


Figure 1. UV spectrum of fluoromethoxycarbene (**1b**) in a nitrogen matrix at 15 K. This is a difference spectrum (after irradiation minus before irradiation of matrix-isolated diazirine **2b**) that emphasizes the FCOMe maximum at 245 nm. The negative absorptions at 330–370 nm are due to diazirine **2b**, inverted by the difference procedure.

Results and Discussion

Carbene Generation. $(MeO)_2C$ and FCOMe (**1**) were both generated from the corresponding diazirines (**2**) by photolysis or thermolysis, eq 1. The diazirines, in turn, were prepared by



(1)

2 **1**

a, X = OMe; b, X = F; c, X = Cl

subjecting chloromethoxydiazirine (**2c**) to a diazirine exchange reaction[4] with methoxide (for **2a**[11]) or by exchanging bromomethoxydiazirine (**2**, X = Br) with fluoride (for **2b**[12]). Chloromethoxydiazirine was obtained by the Graham oxidation of *O*-methylisourea tosylate.[13]

Steady-state photolysis or LFP of **2a** gave rise to $(MeO)_2C$, λ_{max} 255 nm, in a 3-methylpentane glass at 77 K or in pentane solution at ambient temperature, respectively. Details of these experiments and spectra have been published.[11,14]

A matrix isolation spectrum of FCOMe was obtained by irradiation of **2b** in a nitrogen matrix. Thus, 366-nm photolysis of diazirine **2b**, matrix isolated 1:700 in N_2 at 12 K, gave FCOMe that was characterized by IR and UV spectroscopy. Carbene **1b** exhibited IR bands at (relative intensity) 1476 (1.0), 1472 (2.6), 1462 (4.0), 1453 (1.0), 1447 (1.5), 1442 (18.9), 1095 (3.8), 1022 (1.3), 1018 (2.7), 1006 (11.1), 868 (3.0), and 603 (3.9) cm^{-1}.

The photochemical behavior of **1b** was similar to that previously reported for chloromethoxycarbene, **1c**.[15] Irradiation of matrix-isolated FCOMe at $\lambda < 280$ nm destroyed the carbene's IR bands and fostered the growth of absorptions assigned (by comparisons with authentic samples) to acetylfluoride, ketene, HF, CO, and CH_3F. FCOMe could also be generated in a more concentrated ($\mathbf{2b}:N_2 = 1:300$) matrix at 12 K. Warming this matrix to 29 K caused a considerable decrease in the carbene's IR bands, together with an increase in bands due to MeOCF=CFOMe, the dimer of **1b** (again identified by comparison to an authentic sample).[12]

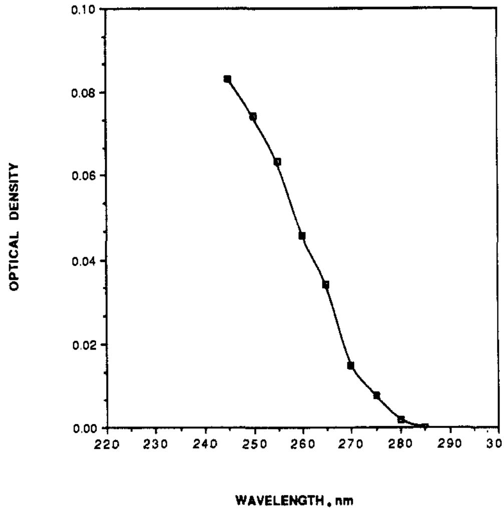
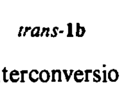


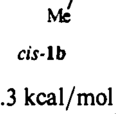
Figure 2. Point-by-point transient spectrum of fluoromethoxycarbene obtained by LFP in pentane at ambient temperature. The optical density scale is in arbitary units. See text for discussion.

The UV spectrum of irradiated, matrix-isolated diazirine **2b** revealed a photolabile absorption with λ_{max} at 245 nm (Figure 1) that we assigned to FCOMe on the basis of several experiments. The IR and UV bands of carbene **1b** grew in simultaneously on irradiation of matrices containing diazirine **2b**, and they also were destroyed in tandem on subsequent photolysis at shorter wavelengths. Most importantly, the "action spectrum" for the photodestruction of the IR bands attributed to carbene **1b** approximated its UV spectrum. Although variations in the intensity of the Hg lamp/monochromator system utilized for irradiations precluded a quantitative assessment of the wavelength dependence of photolysis of **1b**, the carbene IR bands were stable to wavelengths ≥ 280 nm and more labile to irradiation at 250 nm (offset from the major 254 nm emission line) than to irradiation at 235 or 265 nm. Moreover, the wavelength dependence for selective destruction of IR bands assignable to the cis and trans isomers of the carbene support the assignments (see below). Finally, no IR bands were observed in the 2000–2100-cm^{-1} region that is characteristic for diazo compounds.

The observed λ_{max} of matrix-isolated FCOMe (245 nm) is also in reasonable agreement with calculated values. Thus, we carried out ab initio and semiempirical INDO/S molecular orbital calculations on the electronic structure of **1b**.[16] FCOMe should exist as trans and cis ground-state singlets, with *trans*-**1b** calculated only 1.1 kcal/mol lower in energy then *cis*-**1b**.[17] The activation



trans-**1b**



cis-**1b**

barrier to their interconversion lies 21.3 kcal/mol above *trans*-**1b**, indicative of substantial double bond character in the carbene's –C–O– bond due to oxygen lone pair–carbene 2p (LUMO) delocalization. We also calculate $S_0 \rightarrow S_1$ ($\sigma^2 \rightarrow \sigma^1p^1$) transitions

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(11) (a) Moss, R. A. Włostowski, M.; Shen, S.; Krogh-Jespersen, K.; Matro, A. *J. Am. Chem. Soc.* **1988**, *110*, 4443. (b) Note that the $(MeO)_2C$ absorption at 255 nm cannot be contaminated by absorption from the protonated carbene, that is, cation $(MeO)_3CH^+$. The cation has no allowed transitions above 200 nm: Ramsey, B. G.; Taft, R. W. *J. Am. Chem. Soc.* **1966**, *88*, 3058. We calculate (see ref 16, below) the UV absorption of $(MeO)_3CH^+$ at ~182 nm. Additionally, we see no absorptions that could be attributed to dimethoxydiazomethane upon LFP of diazirine **2a**.

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(14) The XeF excimer laser afforded 14 ns pulses at 50–100 mJ and 351 nm. The shutter in front of the 1000 W Xe monitoring lamp was adjusted to remain open for 220 ms immediately after the laser pulse. Details of our LFP system are described in the following: Moss, R. A.; Shen, S.; Hadel, L. M.; Kmiecik-Ławrynowicz, G.; Włostowska, J.; Krogh-Jespersen, K. *J. Am. Chem. Soc.* **1987**, *109*, 4341.

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(16) Ab initio calculations employed the GAUSSIAN 86 series of programs: Frisch, M. et al., Carnegie-Mellon Publishing Unit: Pittsburgh, PA. Geometries were optimized at the HF/6-31G* level for **1b**, **1a**, and CF_2, and relative energies were obtained at the MP3/6-31G*//6-31G* level and corrected for zero-point vibrational energies at the HF/3-21G level. The INDO/S calculations used the HF/6-31G* geometries, the Pariser approximation for two-electron integrals, and full singly excited configuration interaction. Procedures and parameters were the same as those used previously[11] and are fully described in the following: Zerner, M. C.; Bacon, A. D. *Theor. Chim. Acta (Berlin)* **1979**, *53*, 21. Ridley, J.; Zerner, M. *Ibid.* **1973**, *32*, 111.

(17) For corresponding calculations on $(MeO)_2C$, see ref 11. The singlet state of *trans*-FCOMe is calculated to lie 69.4 kcal/mol *below* the corresponding triplet.

Table I. Pseudo-First-Order Rate Constants for Reactions of Methoxycarbenes with 1 M Hydroxylic Substrates[a]

substrate	pK_a[b]	concn range, M	order[c]	k_ψ, s^{-1}	
				$(MeO)_2C$	FCOMe
CH_3CH_2OH	15.90[d]	0.26–2.4	1	$3.2 \pm 0.9_3 \times 10^4$[e]	f
CH_3OH	15.54[d]	0.09–1.0	1	$8.8 \pm 0.2_2 \times 10^4$	f
$ClCH_2CH_2OH$	14.31[d]	0.23–2.1	2	$9.1 \pm 1.0_4 \times 10^5$	g
FCH_2CH_2OH	14.20[h]	0.26–2.4	2	$2.3 \pm 0.2_4 \times 10^6$	f
F_3CCH_2OH	12.37[d]	0.14–0.53	2	$6.3 \pm 0.9_2 \times 10^7$	i
$(F_3C)_2CHOH$	9.30[j]	0.004–0.03	1	$6.7 \pm 0.7_2 \times 10^8$	$9.1 \pm 1.2_2 \times 10^3$[k]
CH_3COOH	4.76[l]	0.0004–0.0009	1	$2.4 \pm 0.4_2 \times 10^9$	$2.0 \pm 0.2_2 \times 10^7$[m]

[a] In CH_3CN solution at 20 °C. [b] In aqueous solution, see text. [c] Apparent kinetic order in substrate from the correlation of $k_\psi^{(MeO)_2C}$ vs [substrate] over the indicated concentration range. k_ψ data are reported at 1 M ROH. [d] Reference 18a. [e] Subscript indicates the number of repetitions; errors are average deviations. [f] Kinetic quenching was not observed, even in 80% substrate/CH_3CN. [g] Not done. [h] Reference 18b. [i] No quenching was observed at 2 M TFE. [j] Reference 18c. [k] Apparently second order in substrate, 0–2.4 M. [l] Reference 18d. [m] Apparently 1.5 order in substrate, 0.11–0.56 M.

for *trans*-**1b** and *cis*-**1b** at 254 nm (*f* [oscillator strength] = 0.06) and 240 nm (*f* = 0.08), respectively. These calculated absorption maxima bracket the observed matrix λ_{max} (245 nm). Although two resolved absorptions are not seen in the matrix UV spectrum, irradiation at 260 nm selectively destroys the IR bands independently assigned to *trans*-**1b** (by analogy to **1c**[15]), whereas 235-nm photolysis is selective for *cis*-**1b**. Thus, both "isomers" of FCOMe appear to be present and contribute to the broad optical absorption band. The full-matrix spectroscopic analysis of **1b** will appear elsewhere; the apparatus and general experimental procedures employed here have been described.[15]

Pulsed laser photolysis at 351 nm[14] of a pentane solution of **2b** gave rise to a transient absorption in the 245–280-nm region that we attribute to FCOMe; see Figure 2. This band is in good agreement with both the matrix isolated and calculated carbene absorption maxima; see above. Diazirine **2b** has λ_{max} (pentane) 332 sh, 348, and 364 nm,[12] and it is this band system that is irradiated by the laser. However, there is also a strong (unassigned) absorption at ~210 nm present in our diazirine preparation. In order to obtain a sufficiently intense FCOMe signal for the kinetic studies, we needed [**2b**] such that $A_{350} \sim 1.0$. Under these conditions, the trailing edge of the 210-nm absorption interfered with the carbene absorption, so that we could only observe the long wavelength half of this band (Figure 2).

Nevertheless, monitoring LFP generated FCOMe in pentane at 250 nm, afforded A vs time data from which $\tau_{1/2} \sim 1$ ms. Under comparable conditions, the half-lifetime of $(MeO)_2C$ is ~2 ms.[11] The decay of MeOCF in pentane [as is the case for $(MeO)_2C$] is apparently second order; $1/A$ was linear with time. Thermal decomposition of concentrated **2b** in decane at 80 °C is known to give the carbene dimer (MeOCF═CFOMe, 57%) and some azine (MeOCF═N—N═CFOMe, 13%).[12] Conventional photolysis (λ > 300 nm) of a concentrated solution of **2b** in pentane also afforded dimer and azine in a ratio of ~3:1.

Quenching Experiments. Kinetics. $(MeO)_2C$ and FCOMe were generated in CH_3CN solution by LFP and quenched with a variety of hydroxylic substrates. These included ethanol (EtOH), methanol (MeOH), 2-chloroethanol (ClEtOH), 2-fluoroethanol (FEtOH), trifluoroethanol (TFE), hexafluoroisopropyl alcohol (HFP), and acetic acid (HOAc). The alcohols were all of good initial purity, were dried over appropriate dessicants, and fractionally distilled before use (except for anhydrous EtOH, which was used as received from a previously sealed bottle). Acetonitrile was spectro-grade, freshly distilled, and stored over molecular sieves.

LFP[14] of diazirine **2a** at 20 °C in CH_3CN solutions of the hydroxylic substrates gave rise in each case to the transient absorption of **1a**, $(MeO)_2C$, that was monitored at 255 nm.[11b] With EtOH, MeOH, and HFP, correlations of the pseudo-first-order rate constants for carbene decay were linear with [ROH] in the examined concentration ranges (see Table I). With ClEtOH, FEtOH, and TFE, however, the correlations were curved concave upward in a manner similar to that observed in the quenching of *p*-anisylchlorocarbene by MeOH in CH_3CN.[8] Curvatures of this kind have been attributed to competitive reactions of the carbene with alcohol oligomers (faster) and monomers (slower) in a proportion that changed with changing [ROH].[8]

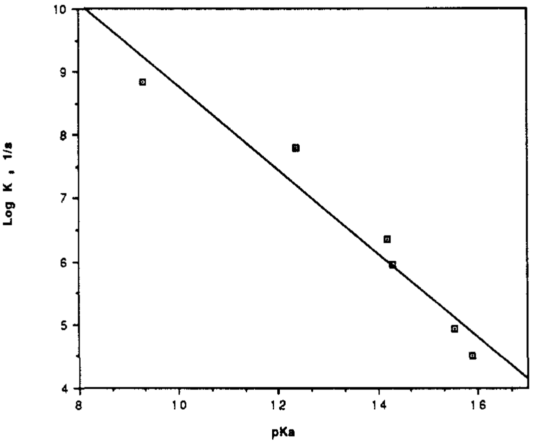

Figure 3. Brønsted correlation between log k_ψ (s^{-1}) for the quenching of $(MeO)_2C$ by 1 M ROH in CH_3CN and the (aqueous) pK_a of ROH, cf., Table I and text. From left to right, the points represent hexafluoroisopropyl alcohol, trifluoroethanol, 2-fluoroethanol, 2-chloroethanol, methanol, and ethanol. The slope, α, is –0.66.

Without detailed analyses of the monomer/dimer/oligomer equilibria for each alcohol in CH_3CN, we cannot extract the individual rate constants for carbene/monomer and carbene/oligomer reactions. Accordingly, we present in Table I the observed (or extrapolated) pseudo-first-order rate constants for $(MeO)_2C$ decay at 1 M alcohol in CH_3CN solution, reflecting the carbene's reactivity as a function of the alcohol's structure and acidity. We also display pK_a values for *aqueous* solutions of the alcohols.[18] Of course, these values are not directly transferable to CH_3CN solution,[19] although, at least for carboxylic acids and phenols, $pK_a(CH_3CN) - pK_a(H_2O) \sim 14.0$.[20]

Figure 3 is a Brønsted plot of log k_ψ vs (aqueous) pK_a for the reactions of $(MeO)_2C$ with 1 M ROH in CH_3CN. The correlation covers >6 p*K* units and >4 orders of magnitude in k_ψ. Despite some curvature, there is a good approximation to linearity: the slope of the correlation, α, is –0.66, and the correlation coefficient, *r*, is 0.94, significant at the 99% confidence level. The appreciable value of α suggests a substantial degree of proton transfer between ROH and $(MeO)_2C$ in the reaction's rate-determining transition state.[21] Although we should not attach further quantitative significance to α, its magnitude is consistent with the reported primary kinetic isotope effect for the reaction of $(MeO)_2C$ with

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(21) Reference 18d, p 226f.

MeOH (3.3 ± 0.5),[9] that is also in accord with significant proton transfer.

The kinetic data for (MeO)$_2$C/HOAc has been omitted from the Brønsted correlation of Figure 3 for two reasons. First, HOAc is not an alcohol, and its pK_a differs by >4 units from that of the nearest alcohol (HFP) of Table I. Second, the extrapolated bimolecular rate constant for (MeO)$_2$C/HOAc from the ROH correlation is 1.6×10^{12} M^{-1} s^{-1}, which clearly exceeds diffusion control. Indeed, the observed k_ψ, 2.4×10^9 s^{-1}, may already be influenced by diffusion.

LFP of diazirine **2b** at 20 °C in CH$_3$CN solutions of the same substrates gave rise to FCOMe. The "long" wavelength portion of this transient's absorption (see above and Figure 2) was monitored at 255 nm as a function of time. FCOMe was surprisingly "inert" to alcohols. EtOH, MeOH, FEtOH, and TFE failed to quench the carbene at 1 M ROH in CH$_3$CN. Only with HFP and HOAc was FCOMe competitively quenched relative to its decay by dimerization or other pathways. The kinetic data appear in Table I. The extraordinary unreactivity of FCOMe toward MeOH, observed in the LFP experiments, is consistent with the carbene's behavior in photoacoustic calorimetry experiments (see below), where quenching by MeOH is not observed on the PAC time scale ($\tau_{\mathrm{FCOMe}} > 2$ μs in pure MeOH). As indicated in Table I, and discussed below, the reactivity of FCOMe toward ROH is *generally* much lower than that of (MeO)$_2$C.

The reactions of (MeO)$_2$C with MeOH(D) in *pentane* lead to a primary kinetic isotope effect (KIE) of 3.3 ± 0.5.[9] FCOMe is not quenched rapidly enough by MeOH to determine a KIE by LFP. However, its quenching by AcOH is in an accessible range.[22] We find rate constants of $1.69 \pm 0.06_2 \times 10^7$ and $8.66 \pm 0.94_2 \times 10^6$ M^{-1} s^{-1} for reactions of FCOMe with AcOH or AcOD, respectively, in pentane at 20 °C, leading to $k_H/k_D = 1.95 \pm 0.21_2$. This is a significant KIE, suggestive of some proton transfer in the FCOMe/AcOH reaction transition state.[23,24]

Quenching Experiments. Products. For (MeO)$_2$C product studies, a 3-fold molar excess of ROH substrate, based on the *O*-methylisourea precursor of diazirine **2c** (the precursor, in turn, of diazirine **2a**), was mixed with a pentane solution of **2a**. This diazirine was decomposed thermally (22 °C, 2.5 h, dark), and the orthoformate product was recovered from the pentane solution after a routine workup. The procedure for the FCOMe study was similar; the molar ROH excesses (again based on *O*-methylisourea) were 2.5-fold with HOAc or TFE or 8-fold with MeOH or HFP. Dark thermolyses of diazirine **2b** were carried out in sealed tubes at 80 °C, with stirring, for 5 h. Pentane extracts of the final reaction product mixtures were distilled on a spinning band column.

Reactions of (MeO)$_2$C with MeOH,[9,11] ClEtOH, FEtOH, TFE, and HFP provided the formal O–H insertion products **3**–**7**, respectively, that were purified by distillation and/or GC and

(MeO)$_2$CHOR (MeO)$_2$CHF
3, R = Me[9,11] **8**
4, R = CH$_2$CH$_2$Cl
5, R = CH$_2$CH$_2$F[25]
6, R = CH$_2$CF$_3$
7, R = CH(CF$_3$)$_2$

generally identified by NMR and (exact) mass spectroscopy. Photolytic generation (λ > 300 nm) of (MeO)$_2$C in MeOH, TFE, and HFP also gave the insertion products, but the thermolysis procedure was simpler. The absolute yields of the orthoformates were low, ranging from 7% for **4** through 30% for **6**, but this is partly due to the calculation of the yield based on the *O*-methylisourea diazirine precursor. Thus, *O*-methylisourea tosylate was first oxidized with HOCl to diazirine **2c**,[13] this was converted with methoxide ion to diazirine **2a**,[11] and the latter was decomposed to (MeO)$_2$C in a particular alcohol. The final yield of orthoformate then represents the aggregate yield of a three-step sequence. In the specific case of trimethyl orthoformate, **3**, where the yield was directly determined on **2a**, more than 90% of orthoformate was obtained.[11]

The details of product yields and spectra appear in the Experimental Section. As an additional structure proof, orthoformates **4**–**7** were each converted to **3** by stirring with MeOH/HOAc (analysis by GC). The product of the (MeO)$_2$C/HOAc reaction was not specifically characterized.

FCOMe was reacted on preparative scale with MeOH, TFE, HFP, and AcOH. Recall that kinetic evidence for the quenching of FCOMe was obtained only with HFP and HOAc (see above). Nevertheless, some indication of appropriate product formation was found with FCOMe and MeOH, TFE, or HFP. A stable product could not be isolated from the FCOMe/HOAc reaction.

In the FCOMe/MeOH reaction, we obtained 15% (based on *O*-methylisourea) of a ~3:1 mixture of (possibly) **8** and trimethyl orthoformate, **3**. Product **8** was also obtained from the photolysis (λ > 300 nm, 3.5 h, 25 °C) of diazirine **2b** in 8-fold excess MeOH. Compound **8** ($\delta_{\mathrm{OMe}}{}^{\mathrm{CDCl_3}}$ 3.40) was very unstable in MeOH and readily converted to **3** ($\delta_{\mathrm{OMe}}{}^{\mathrm{CDCl_3}}$ 3.20) by a F/OMe exchange that was probably autocatalytic, making use of the HF generated in the exchange. Either raising the reaction temperature (to 100 °C) or lengthening the reaction time (>5 h) led mainly or exclusively to **3**, at the expense of **8**. Heating the crude **8**/**3** mixture (80 °C/4 h), or treating it with NaOMe (25 °C/24 h), converted **8** to **3** completely.

A GC-MS of **8** showed (M$^+$ − F) [(MeO)$_2$CH$^+$] at *m*/*e* 75, but a parent ion was not observed. ^{19}F NMR spectroscopy (CDCl$_3$, external CF$_3$COOH reference) showed only a singlet at −33.2 ppm that we attribute to released fluoride.

With FCOMe and TFE, we isolated ~6% of **9** that presumably arose from **10** by exchange with an additional molecule of TFE.

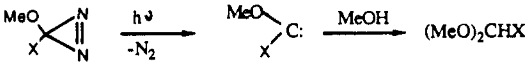
(CF$_3$CH$_2$O)$_2$CHOMe CF$_3$CH$_2$OCHFOMe
9 **10**

A similar result was obtained upon photolysis of diazirine **2b** in TFE. The structure of **9** was established by ^{1}H and ^{19}F NMR spectroscopy and by GC-MS, where an exact mass was obtained on the ion derived from **9** by loss of MeO.

With HFP as substrate, FCOMe gave ~5% of a mixture of **11**, the formal insertion product, and **12**, the HFP/HF exchange product derived from **11**. Compound **11** was identified by GC-MS; an exact mass was obtained for the (M$^+$ − F) ion. The (M$^+$ − OCH$_3$) ion was also observed at 0.33 times the intensity of (M$^+$ − F). Orthoformate **12** was also substantiated by GC-MS, with an exact mass on (M$^+$ − OCH$_3$); (M$^+$ − H) was observed at a low relative intensity (0.06). ^{1}H and ^{19}F NMR spectroscopy in CDCl$_3$ provided good evidence for **12**, but **11** was not present in a high enough concentration for definitive analysis.

(CF$_3$)$_2$CHOCHFOMe [(CF$_3$)$_2$CHO]$_2$CHOCH$_3$
11 **12**

Photoacoustic Calorimetry (PAC). Photoexcitation of diazirines **2a**–**c** affords the singlet carbenes **1a**–**c**. In methanol, these carbenes "insert" into the O–H bond, producing methoxy compounds **3a**–**c**; see above, refs 10–12, and eq 2. In pentane, the carbenes undergo bimolecular reactions to give dimers, azines, or other products.[10–12]



(2)

2 **1** **3**

a, X = OMe; b, X = F; c, X = Cl

PAC provides kinetic and enthalpic information about transient intermediates.[10,26–28] Deconvolution of the experimental acoustic

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[22] In contrast, the reactions of (MeO)$_2$C with AcOH(D) in pentane at 20 °C approach diffusion control, with $k_H = 2.91 \pm 0.13 \times 10^9$ and $k_D = 2.84 \times 10^9$ M^{-1} s^{-1}, affording an isotope effect of unity.

[23] Lowry, T. H.; Richardson, K. S. *Mechanism and Theory in Organic Chemistry*, 3rd ed.; Harper and Row: New York, 1987; pp 233–238.

[24] Note that the reactions of arylchlorocarbenes with AcOH, like those of (MeO)$_2$C, have $k_2 > 10^9$ M^{-1} s^{-1} and would presumably show no KIE cf.: Griller, D.; Liu, M. T. H.; Montgomery, C. R.; Scaiano, J. C.; Wong, P. C. *J. Org. Chem.* **1983**, *48*, 1359.

[25] In this case, MeOCH(OCH$_2$CH$_2$F)$_2$ was also formed, presumably by FCH$_2$CH$_2$OH/MeOH exchange of the initially produced **5**. Analogous products were not generally observed with the other orthoformates.

Table II. Experimental Heats of Reaction Determined by PAC[a,b]

carbene	$\Delta H(\mathbf{2} \rightarrow \mathbf{3})^c$	$\Delta H(\mathbf{2} \times \mathbf{1})^d$	$\Delta H(\mathbf{1} \rightarrow \mathbf{3})$
$(MeO)_2C$ (**1a**)	−68.3 (3.7)[e,f]	−43.5 (2.6)	−24.8 ± 4.5
FCOMe (**1b**)	*g*	−35.1 (3.2)	
ClCOMe (**1c**)	−71.1 (3.5)[f,h]	−39.9 (2.9)	−31.2 ± 4.5

[a] See text and ref 10 for experimental details. See eq 2 for structure numbering. [b] Values are in kcal/mol. [c] In methanol. [d] In pentane. [e] Values are from at least four separate runs; the errors in parentheses are 1σ. The errors associated with $\Delta H(\mathbf{1} \rightarrow \mathbf{3})$ are propagated. [f] This represents the total enthalpy of reaction for the two heat depositions, $\mathbf{2} \rightarrow \mathbf{1} \rightarrow \mathbf{3}$; see text and eq 2. [g] Not resolved by PAC; see text. [h] From ref 10.

waveforms measures the amplitude and time evolution of the heat deposition of the system; details of this method have been previously reported.[10,26,27] Irradiations of **2a–c** in pentane afford single heat depositions, ≤10 ns, that reflect the formation of carbenes **1a–c**. The measured reaction enthalpies, $\Delta H(\mathbf{2} \rightarrow \mathbf{1})$, correspond to **2a–c** → **1a–c**. No second heat depositions are observed by PAC, suggesting that the lifetimes of the carbenes are ≥2 μs in pentane (at $\sim 10^{-5}$ M), in agreement with the LFP studies reported above that indicate long half-lifetimes for dilute pentane solutions of (e.g.) **1a** ($\tau_{1/2} \sim 2$ ms)[11] and **1b** ($\tau_{1/2} \sim 1$ ms).

Irradiation of **2a** in neat MeOH results in a single heat deposition, ≤10 ns. However, this includes both the initial formation of carbene **1a** as well as its subsequent insertion into the O–H bond. The measured reaction enthalpy, $\Delta H(\mathbf{2} \rightarrow \mathbf{3})$, therefore corresponds to the two-step process, **2a** → **3a**, eq 2. The *difference* between the reaction enthalpy in pentane, $\Delta H(\mathbf{2} \rightarrow \mathbf{1})$, and in MeOH, $\Delta H(\mathbf{2} \rightarrow \mathbf{3})$, corresponds to $\Delta H(\mathbf{1} \rightarrow \mathbf{3})$, the enthalpy of the carbene/O–H reaction. The enthalpy data for the photochemical reactions of **2a**, as determined by PAC, appear in Table II.[29,30]

Irradiation of diazirine **2b** in MeOH also leads to a single heat deposition, ≤10 ns; however, the observed reaction enthalpy is *equal* to that found in pentane. This implies that the formation of product **3b** from FCOMe does not occur on the time scale of the PAC experiment ($\tau \geq 2$ μs), in agreement with the LFP results (Table I). Assuming first-order MeOH dependence, the bimolecular rate constant for the MeOH/FCOMe reaction is $\leq 10^4$ M^{-1} s^{-1}.

Table III. Heats of Formation and Stabilities of Several Carbenes[a]

carbene	ΔH_f, kcal/mol	ΔE_{stab},[b] kcal/mol
CH_2	102[c]	0
ClCOMe	−22[d]	60
CF_2	−46[e]	63
FCOMe	−53[f,g]	74
$(MeO)_2C$	−61[g,h]	80

[a] Values are rounded to the nearest kcal/mol. [b] From ref 36. [c] From ref 37. [d] From ref 10. [e] See refs 33–35 and text. [f] We cite the semiempirical value; see text. [g] This work; see ref 32b. [h] Estimated error, ±4.5 kcal/mol.

Irradiation of **2c** in MeOH results in two time-resolved heat depositions that reflect carbene formation, $\Delta H(\mathbf{2} \rightarrow \mathbf{1})$, and subsequent O–H insertion, $\Delta H(\mathbf{1} \rightarrow \mathbf{3})$.[10] The lifetime of **1c** in neat MeOH is ~470 ns. This reaction is much slower than reactions of $(MeO)_2C$. Thus, $k_2^{(MeO)_2C}$ in MeOH/pentane is 6.4×10^6 M^{-1} s^{-1},[9] whereas, in MeOH/CH_3CN, LFP k_ψ values for $(MeO)_2C$ decay increase steadily from $\sim 9 \times 10^4$ s^{-1} at 1 M MeOH (Table I) to 2×10^7 s^{-1} at 15.5 M MeOH. At [MeOH] = 20 or 23 M, the carbene is quenched so rapidly that its UV absorption cannot be seen, so that $\tau \leq 20$ ns for $(MeO)_2C$ in pure MeOH. The reaction of $(MeO)_2C$ with MeOH is therefore faster than that of ClCOMe[10] and very much faster than the FCOMe/MeOH reaction, where quenching is not observed in 80% MeOH/CH_3CN (Table I).

The heats of formation of $(MeO)_2C$ and ClCOMe,[10] $\Delta H_f(\mathbf{1})$, can be calculated by using the $\Delta H(\mathbf{1} \rightarrow \mathbf{3})$ values (Table II) and the heats of formation of MeOH, -48.2 kcal/mol,[31] and those of insertion products **3a** and **3c**.[32a] This procedure affords $\Delta H_f[(MeO)_2C] = -61.1 \pm 4.5$ kcal/mol and $\Delta H_f(ClCOMe) = -21.6 \pm 4.5$ kcal/mol.[10]

The value of $\Delta H_f(FCOMe)$ cannot be similarly obtained because the PAC experiment does not resolve the heat of formation of FCOMe with MeOH. However, we can *estimate* $\Delta H_f(FCOMe)$ in two ways. First, we can calculate ΔH_f for diazirine **2b** by the semiempirical MNDO method;[32a] we obtain -17.8 kcal/mol. This value, together with the observed heat of reaction, $\Delta H(\mathbf{2b} \rightarrow \mathbf{1b}) = -35.1$ (Table II), gives us $\Delta H_f(FCOMe) \sim -53 \pm 3$ kcal/mol.

In a second approach, we estimate $\Delta H_f(FCOMe)$ from the ab initio computed enthalpy change[16] (-4.1 kcal/mol for *trans*-**1b**) that accompanies the isodesmic reaction, eq 3, and the experimentally determined heats of formation of CF_2 (−46 kcal/mol)[33-35]

$$CF_2 + (MeO)_2C \rightarrow 2FCOMe \qquad (3)$$

and $(MeO)_2C$ (−61 kcal/mol, above). This leads to $\Delta H_f(FCOMe) = -56 \pm 3$ kcal/mol, in good agreement with the first estimate.

The sequence of stabilities of the carbenes considered here is $(MeO)_2C$ > FCOMe > CF_2 > ClCOMe, with $(MeO)_2C$ most stable. This order is based on ΔE_{stab}, the carbene stabilization energy relative to CH_2, where ΔE_{stab} is defined as the negative of the HF/4-31G ab initio calculated energy of the isodesmic reaction shown in eq 4.[36] The calculated ΔE_{stab}, together with

$$CH_2 + CH_3X + CH_3Y \xrightarrow{-\Delta E_{stab}} CXY + 2CH_4 \qquad (4)$$

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(26) (a) LaVilla, J. A.; Goodman, J. L. *Chem. Phys. Lett.* **1987**, *141*, 149. (b) Herman, M. S.; Goodman, J. L. *J. Am. Chem. Soc.* **1988**, *110*, 2681. (c) LaVilla, J. A.; Goodman, J. L. *Tetrahedron Lett.* **1988**, *29*, 2623. (d) Herman, M. S.; Goodman, J. L. *J. Am. Chem. Soc.* **1989**, *111*, 1849.

(27) (a) Rudzki, J. E.; Goodman, J. L.; Peters, K. S. *J. Am. Chem. Soc.* **1985**, *107*, 7849. (b) Westrick, J. A.; Goodman, J. L.; Peters, K. S. *Biochemistry* **1987**, *26*, 8313.

(28) (a) Heihoff, K.; Braslavsky, S. E.; Schaffner, K. *Biochemistry* **1987**, *26*, 1422. (b) Kanabus-Kaminska, J. M.; Hawari, J. A.; Griller, D.; Chatgilialoglu, C. *J. Am. Chem. Soc.* **1987**, *109*, 5267. (c) Mulder, P.; Saastad, O. W.; Griller, D. *Ibid.* **1988**, *110*, 4090. (d) Ni, T.; Caldwell, R. A.; Melton, L. A. *Ibid.* **1989**, *111*, 457.

(29) (a) PAC measures the total volume change of the associated reaction. This includes volume changes from thermal (ΔV_{th}) and reaction volume (ΔV_{rx}) origins. The ΔV_{rx} contribution has previously been neglected,[10,26a-c,27,28] but it can be significant.[26d] We are presently investigating its magnitude. ΔV_{rx} for $\mathbf{2} \rightarrow \mathbf{1}$ should be positive, which would give an erroneously large value for $\Delta H(\mathbf{2} \rightarrow \mathbf{1})$. However, in $\mathbf{2} \rightarrow \mathbf{3}$, ΔV_{rx} should be significantly smaller, so that $\Delta H(\mathbf{2} \rightarrow \mathbf{3})$ should accurately reflect the thermal volume change. (b) The PAC reaction enthalpies include the differential heat of solvation between reactants and products. Although the heats of solvation of **2a–c** and **3a–c** are probably small, those of **1a–c** might be significant. Consequently, the calculated values of $\Delta H_f(\mathbf{1})$ (see below) could be less than values obtained in the gas phase.

(30) The quantum yields for disappearance of diazirines **2b** and **2c** are unity,[10] but the value cannot be readily determined for the thermally labile diazirine **2a**. It is assumed that the decompositions of diazirines **2a–c** afford carbenes **1a–c** within 10 ns and with unit efficiency. In the case of **2a**, this is supported by the high yield of the MeOH trapping product (>90%) of carbene **1a**. Alternative pathways to the products are possible, however, and could affect the PAC results if (i) the quantum yield is appreciable or (ii) an intermediate other than the carbene is generated that has lifetime >2 μs. A conceivable alternative intermediate is a diazoalkane, formed by diazirine → diazoalkane photoisomerization. However, this isomerization has not been observed for diazirines **2a–c** by matrix IR, UV, or LFP methods: see, for example, ref 15.

(31) Cox, J. D.; Pilcher, G. *Thermochemistry of Organic and Organometallic Compounds*; Academic Press: London, 1970.

(32) (a) These values are calculated by using the MNDO method (QCPE program 506), leading to ΔH_f (**3a**, **3b**, and **3c**) = −134.1, −144.9, and −101.0 kcal/mol, respectively. (b) The *experimental* value of $\Delta H_f(\mathbf{3a})$ is −127.7 kcal/mol (gas phase): Hine, J.; Klueppel, A. W. *J. Am. Chem. Soc.* **1973**, *96*, 2924. If this value is used to calculate $\Delta H_f(\mathbf{1a})$, we obtain $\Delta H_f[(MeO)_2C] = -54.7 \pm 4.5$ kcal/mol. In Table III and in the discussion, we use instead the semiempirical value for $\Delta H_f(\mathbf{1a})$ (~ −61 kcal/mol), based on the MNDO ΔH_f for **3a**.[32a] This provides consistency in comparisons with the other carbene heats of formation, where MNDO values had to be used for $\Delta H_f(\mathbf{3})$.[10]

(33) There has been much discussion of this value. We use here an average (−46 ± 3 kcal/mol) of Beauchamp's value (−44 ± 2 kcal/mol)[34] and Liebman's value (−49 ± 3 kcal/mol).[35] See these papers for extensive discussion and tabulations of literature values.

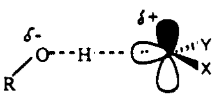
(34) Berman, D. W.; Bomse, D. S.; Beauchamp, J. L. *Int. J. Mass Spect. Ion Physics* **1981**, *39*, 263.

(35) Lias, S. G.; Karpas, Z.; Liebman, J. F. *J. Am. Chem. Soc.* **1985**, *107*, 6089.

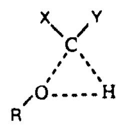
the empirical or semiempirical ΔH_f values are collected in Table III. What is striking about a comparison of the stability and kinetic data is that the ordering of k_2 for reaction with MeOH is $(MeO)_2C$ > ClCOMe > FCOMe, where $(MeO)_2C$, expected on the basis of its stability (Table III) to be the *least* reactive carbene, is in fact the *most* reactive.

As noted at the outset, there are several possible mechanisms for the O–H "insertion" reactions of carbenes. Relatively unstable, predominantly electrophilic carbenes such as ClCPh[38] probably react with the nucleophile MeOH by a rate determining ylide-type, carbene LUMO (p)/alcohol HOMO (O–2p) interaction; cf., **13**.

13



14



15

On the other hand, a highly stabilized nucleophilic[6,11] carbene, such as $(MeO)_2C$, probably reacts predominantly by a proton transfer, acid (alcohol)/base (carbene) mechanism that we can represent in the limiting case as **14** (see above and ref 9). Between the "extremes" of transition states **13** and **14**, we can imagine more or less "true" O–H insertion transition states, e.g., 15.

The progression **13**–**15**–**14** represents a gradual change of mechanism in which the availability of a low-lying carbene LUMO for MeOH oxygen 2p electron donation becomes increasingly less important. Just such a progression could be represented by the reactions of ClCOMe, FCOMe, and $(MeO)_2C$, where the calculated 4-31G carbene LUMO (p orbital) energies are 2.46, 3.19, and 4.09 eV, respectively.[36] It may well be that ClCOMe and FCOMe react with MeOH via transition states that approximate **15**, whereas the transition state for the $(MeO)_2C$/MeOH reaction more closely resembles **14**. In this case, one would not expect an exact correlation of the reaction rate constants and carbene stabilities. We hope to test these ideas by experimental and computational methods.

Experimental Section

General Methods. The Rutgers LFP system and methodology have been previously described.[14] The Rochester PAC system has also been described.[10,26] Matrix isolation IR and UV–vis spectra were recorded on Perkin Elmer Models 1800 (FTIR) and Lambda 4 spectrometers, respectively. Mass spectra were determined on a Finnigan MAT 8230 mass spectrometer by Dr. Robert Rosen, Food Science Department, Cook College, Rutgers University. ^1H and ^{19}F NMR spectra were obtained on a Varian VXR-200 instrument. Analytical GC employed a Varian Model 3700 flame ionization unit, fitted with a 12 m × 0.22 mm bonded phase SE-30 vitreous silica capillary column. Preparative GC was carried out on a Varian Model 90-P unit, fitted with a 4 ft × 0.25 in. 10% SF-96 on 90/100 Anakrom ABS column.

3,3-Dimethoxydiazirine (2a).[11] To a cooled solution (0 °C) of 4 g (16.4 mmol) of *O*-methylisourea *p*-toluenesulfonate[39] and 9 g of LiCl in 70 mL of DMSO, in a 1-L, three-necked flask, fitted with a dropping funnel and a connection to a train of vacuum traps (see below), was added 250 mL of 15% aqueous HOCl ("pool chlorine"), saturated with NaCl, over 5 min, with magnetic stirring. The 3-chloro-3-methoxydiazirine (**2c**)[13,40] was pumped out under vacuum (<0.5 mmHg) as it formed, through a train of three traps. The empty trap that was connected to the reaction flask was cooled to −30 °C, the second (empty) trap was cooled to −78 °, and the third trap was charged with 2–3 mL of dry DMF and cooled to −196 °C. A U-tube containing KOH pellets was interposed between the first and second traps. Evacuation was continued for 40 min after addition had been completed. The vacuum train was then isolated from the pump, and the contents of the third trap were very carefully allowed to warm until they just liquified. [**Caution!** The diazirine is explosive. All operations must be carried out behind safety shields.[40]] A 50% yield of **2c** was normally obtained in this reaction.

Diazirine **2c** was converted to the desired **2a** by exchange with NaOMe.[11] Thus, 4.5 g (83 mmol) of fresh NaOMe (Aldrich) was added to 30 mL of DMF that had been distilled and dried over 4Å molecular sieves. The mixture was cooled to −40 °C and stirred magnetically in a 250-mL, three-necked flask that was fitted with a dropping funnel and a low-temperature thermometer. The cold (~0 °C) DMF solution of **2c** was added so as to maintain the reaction temperature below −20 °C. Stirring was continued at −30 to −50 °C for 30 min after addition. The reaction mixture was then diluted with ~30 mL of crushed ice/water and extracted with 3 × 15 mL of cold pentane. The pentane extract was back-washed with ice/water and then dried over anhydrous $CaCl_2$ at −20 °C for 20 min. The pentane solution was then filtered through silica to give ~60% of dimethoxydiazirine (based on **2c**) as a ~0.07 M pentane solution. The UV spectrum of **2a** had λ_{max} 338 sh, 358, and 372 nm.[11]

3-Fluoro-3-methoxydiazirine (2b). The experimental details for the preparation of this diazirine (by fluoride ion exchange on 3-bromo-3-methoxydiazirine, **2**, X = Br) have been published.[12] UV and IR spectra also appear in the literature.[12,41]

Product Studies. Four of the alcohols used in the kinetics and product studies were MeOH (Fisher), ClEtOH (Aldrich), TFE (Aldrich), and HFP (Pfaltz & Bauer). These were initially of >99% purity. They were dried over $CaCl_2$ or 4Å molecular sieves (MeOH) and fractionally distilled before use. FEtOH (95%, Aldrich) was dried over $CaCl_2$ and fractionated on a small spinning band column, bp 103–105 °C (lit.[42] bp 103.4 °C at 757 mmHg). EtOH (Pharmco, anhydrous) was used as received from a fresh bottle. Acetic acid was purified by fractional distillation in the presence of benzene.[43] General procedures for the reactions of the alcohols (and HOAc) with $(MeO)_2C$ and FCOMe are given above in the Results section. Below we describe the details of isolation and identification.

Trimethyl Orthoformate (3)[11] was identified by GC and NMR comparisons to an authentic sample (Aldrich). Its GC retention time at (a column temperature of) 24 °C was 1.01 min.[44]

***β*-Chloroethyl Dimethyl Orthoformate (4).** This orthoformate was purified by preparative GC[45] at 40 °C and obtained in 6.9% overall yield. The capillary GC retention time was 3.32 min at 50 °C. The proton NMR spectrum (δ, $CDCl_3$) revealed 3.36 (s, 6 H, 2MeO), 3.66 (m, 2 H, CH_2Cl), 3.81 (m, 2 H, CH_2O), 5.09 (s, 1 H, CH). GC-MS indicated a small parent ion, but an exact mass could not be obtained. Fragments such as ($M^+ - OCH_3$) and ($M^+ - OCH_2CH_2Cl$) were observed.

***β*-Fluoroethyl Dimethyl Orthoformate (5).** This orthoformate was purified by preparative GC at 50 °C in ~6% overall yield.[25] Its capillary GC retention time was 1.17 min at 50 °C. The ^1H NMR spectrum (δ, $CDCl_3$) showed 3.37 (s, 6 H, 2MeO), 3.81 (d of m, J_{HF} ~ 33 Hz, 2 H, CH_2O), 4.58 (d of m, J_{HF} = 50 Hz, 2 H, CH_2F), 5.09 (s, 1 H, CH). The fluoroethanol exchange product of **5**, $MeOCH(OCH_2CH_2F)_2$, was also formed in about equal amount with **5**. Its ^1H NMR spectrum was very similar to that of **5** but had appropriately altered integral areas. The ^{19}F NMR spectrum of **5** ($CDCl_3$ vs internal $CFCl_3$) showed a multiplet 224.1 ppm upfield from $CFCl_3$. An exact mass for $C_5H_{10}O_3F$ ($M^+ - H$) was calculated for **5** at *m/e* 137.0615, observed, 137.0614. For $MeOCH(OCH_2CH_2F)_2$ and exact mass for $C_6H_{11}O_3F_2$ ($M^+ - H$) was calculated at 169.0676, found, 169.0688.

***β,β,β*-Trifluoroethyl Dimethyl Orthoformate (6).** This material was purified by spinning band distillation at ca. 25 °C/10 mmHg and isolated in 29.7% overall yield. Its capillary GC retention time was 1.01 min at 35 °C. The ^1H NMR spectrum (δ, $CDCl_3$) revealed 3.36 (s, 6 H, 2MeO), 3.96 (q, J_{HF} = 8.8 Hz, 2 H, OCH_2), 5.12 (s, 1 H, CH). The ^{19}F NMR spectrum ($CDCl_3$, vs external CF_3COOH) showed a triplet, J_{HF} = 8.65 Hz, at 1.43 ppm (downfield). An exact mass for $C_5H_8O_3F_3$ ($M^+ - H$) was calculated at *m/e* 173.0426, observed 173.0412.

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(36) Rondan, N. G.; Houk, K. N.; Moss, R. A. *J. Am. Chem. Soc.* **1980**, *102*, 1770.

(37) $\Delta H_f(^1CH_2)$ = 102 kcal/mol: Lengel, R. K.; Zare, R. N. *J. Am. Chem. Soc.* **1978**, *100*, 7495.

(38) The phenylhalocarbenes are predominantly electrophilic,[6] although their nucleophilic properties become apparent in their reactions with electron-poor alkenes: Moss, R. A.; Fan, H.; Hadel, L. M.; Shen, S.; Włostowska, J.; Włostowski, M.; Krogh-Jespersen, K. *Tetrahedron Lett.* **1987**, *28*, 4779. Soundararajan, N.; Platz, M. S.; Jackson, J. E.; Doyle, M. P.; Oon, S.-M.; Liu, M. T. H.; Anand, S. M. *J. Am. Chem. Soc.* **1988**, *110*, 7143.

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

(40) Extreme care is required during cold trap procedures when solid diazirine is present. Thawing should be carried out so as to dissolve the diazirine at the lowest possible temperature. In our hands, *solutions* of the diazirine have never detonated.

(41) Mitsch, R. A.; Neuvar, E. W.; Koshar, R. J.; Dybvig, D. H. *J. Heterocycl. Chem.* **1965**, *2*, 371.

(42) Beilstein, I(1), 170.

(43) Perrin, D. D.; Armarego, W. L. F.; Perrin, D. R. *Purification of Laboratory Chemicals*; Pergamon Press: Oxford, 1966; 56.

(44) All cited GC retention times refer to the SE-30 vitreous silica capillary column described above, operated with an N_2 carrier gas flow of 44 mL/min.

(45) Preparative GC conditions are described in the paragraph labeled General Methods.

1,1,1,3,3,3-Hexafluoro-2-propyl Dimethyl Orthoformate (7). This material was purified by spinning band distillation at ca. 25 °C/10 mmHg and isolated in 22.7% overall yield. Its capillary GC retention time was 3.27 min at 50 °C. The ^{1}H NMR spectrum (δ, $CDCl_3$) showed 3.41 (s, 6 H, 2MeO), 4.57 (m, $J_{HF} = 6$ Hz, 1 H, CH β to $2CF_3$), 5.30 (s, 1 H, orthoformate CH). The ^{19}F NMR spectrum ($CDCl_3$, vs external CF_3COOH) showed a doublet, $J_{HF} = 5.9$ Hz, at 2.32 ppm (downfield). An exact mass for $C_6H_7O_3F_6$ ($M^+ - H$) was calculated at m/e 241.0299, observed 241.0298.

Fluoromethoxydiazirine and MeOH. The likely product of this reaction, dimethoxyfluoromethane, **8**, is described in detail in the Results section.

Bis(β,β,β-trifluoroethyl) Methyl Orthoformate (9). This material was isolated in 5.7% overall yield by pentane extraction. Its capillary GC retention time was 1.33 min at 25 °C. The proton NMR spectrum (δ, $CDCl_3$) showed 3.41 (s, 3 H, OMe), 3.95 (q, $J_{HF} = 8$ Hz, 4 H, $2CH_2$), 5.32 (s, 1 H, CH). The ^{19}F NMR spectrum ($CDCl_3$ vs external CF_3COOH) revealed a triplet, $J_{HF} = 8$ Hz, at 1.65 ppm (downfield). An exact mass for $C_5H_5F_6O_2$ ($M^+ - OCH_3$) was calculated at m/e 211.0194, observed, 211.0196.

(1,1,1,3,3,3-Hexafluoro-2-propoxy)fluoromethoxymethane (11) and bis(1,1,1,3,3,3-hexafluoro-2-propoxy)methoxymethane (12). The reaction product of FCOMe and HFP was isolated by pentane extraction in 4.7% overall yield and contained **11** and **12** (capillary GC retention times 1.02 and 1.62 min, respectively, at 25 °C) in a ratio of ~1:10. Product **11** was present in too small a quantity in the mixture for proper NMR characterization, but an exact mass was calculated for $C_5H_5F_6O_2$ ($M^+ - F$) at m/e 211.0194, observed 211.0188. Compound **12** gave a ^{1}H NMR spectrum (δ, $CDCl_3$) that showed 3.42 (s, 3 H, MeO), 4.65 (m, J_{HF} (apparently) 4 Hz, 2 H, 2CH β to CF_3 groups), 5.65 (s, 1 H, orthoformate CH). The ^{19}F NMR ($CDCl_3$, vs external CF_3COOH) revealed a doublet, $J_{HF} \sim 6$ Hz, at 2.1 ppm (downfield). An exact mass was calculated for $C_7H_3F_{12}O_2$ ($M^+ - OCH_3$) at m/e 346.9941, observed 346.9955.

LFP Studies. A description of the LFP system appears in ref 14. In our early experiments, an aqueous $NiSO_4$ filter was placed in front of the 1000 W Xe monitoring lamp to decrease its output at 340–350 nm and thus to avoid inadvertent photolysis of the diazirine. For the present study, we further optimized the alignments of the laser and monitoring beams, reduced the area of the reaction cuvette surface exposed to the Xe lamp beam by 80%, and enhanced the signal size by ~3 times. We also decreased the open phase of the Uniblitz shutter (in front of the Xe lamp) to 220 ms. Under our new conditions, the $NiSO_4$ filter did not affect the carbene signal size or lifetime; its use was discontinued. Both $(MeO)_2C$ and FCOMe were monitored at 255 nm; their transient spectra appear in ref 11 and Figure 2, respectively. With $(MeO)_2C$ a typical I_0 was ~200 mV, and the transient signal was ~15 mV. For the determination of quenching rate constants, the concentrations of diazirines **2a** and **2b** were usually adjusted to give absorbances of ~1.2 at 350 nm. Rate constants for the quenching of carbenes **1a** and **1b** were obtained from plots of the observed rate constants (s^{-1}) for carbene decay vs the concentration of quenching alcohol or HOAc. Apparent reaction orders were determined from the slopes of log/log plots. Appropriate functions of [ROH] were used when the quenching reaction was not first-order in ROH. Pseudo-first-order rate constants for the decay of the carbenes in 1 M ROH were obtained by direct measurement whenever this was possible or were extrapolated from data obtained at lower [ROH] if necessary. The resulting data are tabulated in Table I.

PAC Studies. The photoacoustic apparatus has been previously described.[10,26] Photolysis was initiated by a nitrogen pumped dye laser (365 nm). The heat deposition was detected by a PZT transducer (Panametrics, Model A125S, 2.25 MHz or homebuilt, ~0.5 mHz). The signal was amplified (Panametrics preamp, Model 5676), digitized (LeCroy 9400), and transferred to a laboratory computer for data analysis. The waveforms were the average of 30–50 laser pulses (<20 μJ). The first 400 points of the acoustic waveform were analyzed by deconvolution methods.[10,26] The optical densities of the calibration and sample compounds were adjusted to be within 1% of each other. Sample absorbances did not change during the experiment. 2-Hydroxybenzophenone (Aldrich) was used as the calibration compound. The results were unaffected by sample concentration or argon degassing of the sample.

The experimental enthalpic parameter, α, is the fraction of incident photon energy lost to the solution in a given heat deposition. This can be converted to the corresponding heat of reaction via $\Delta H_r = (1 - \alpha)E_{h\nu}/\Phi$, where Φ is the reaction quantum yield and $E_{h\nu}$ is the incident laser energy. The quantum yields are determined by using phenylglyoxylic acid actinometry.[46] The disappearance of the diazirine in MeOH was followed by UV–vis spectroscopy (**2c**, 348 nm, $\epsilon = 70$; **2b**, 362 nm, $\epsilon = 43$). A medium pressure Hg lamp with bandpass filters (Corning 0-52 and 7-54) to isolate the appropriate wavelengths was used for photolysis. The quantum yields for the disappearance of **2c** and **2b** were 1.05 ± 0.05 and 1.00 ± 0.02, respectively. The thermal stability of diazirine **2a** was insufficient to permit an accurate determination of its quantum yield, which was assumed to be 1.0 in accord with those of **2b** and **2c**. In the PAC experiments, the diazirines were used immediately upon preparation. Photolyses of **2b** and **2c** were done at 22 °C and that of **2a** was carried out at 11.6 °C. The temperature of the thermostated PAC cell was controlled to ±0.1 °C by a Haake Model 80 circulating bath. Spectrograde MeOH and pentane were used as received.

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Registry No. **1a**, 40480-72-6; **1b**, 63707-32-4; **1c**, 67894-87-5; **2a**, 114980-39-1; **2c**, 4222-27-9; **3**, 149-73-5; **4**, 34265-61-7; **5**, 124992-88-7; **6**, 124992-89-8; **7**, 124992-90-1; **9**, 124992-91-2; **11**, 124992-92-3; **12**, 124992-93-4; TFE, 75-89-8; HFP, 920-66-1; ClEtOH, 107-07-3; FEtOH, 371-62-0; EtOH, 64-17-5; MeOH, 67-56-1; AcOH, 64-19-7; D_2, 7782-39-0.

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