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Complexation of a Singlet Carbene by a Fluoroalkane. Modification of ^{1}:CHCO$_2$Et Selectivity in Perfluorohexane Solution and ab Initio Calculations

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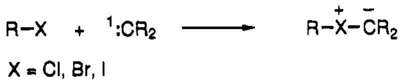
We have compared product distributions from reactions of ^{1}:CH$_2$ with 2,5-dimethylhexane and ^{1}:CHCO$_2$Et with 2,3-dimethylbutane in alkane vs 1:1 pentane–perfluorohexane solution. A solvent effect was observed in the reaction of ^{1}:CHCO$_2$Et, but not ^{1}:CH$_2$. The preference for tertiary/primary C–H insertion by ^{1}:CHCO$_2$Et is 3.97 ± 0.04 in 2,3-dimethylbutane solution and 4.48 ± 0.09 in 1:1 pentane–perfluorohexane solution. There is no change in the stereospecificity of ^{1}:CHCO$_2$Et addition to *cis*-2-pentene in pentane vs 1:1 pentane–perfluorohexane solution, indicating that the observed change in selectivity is probably not due to intersystem crossing to ^{3}:CHCO$_2$Et. Ab initio calculations provide evidence for a possible origin of the solvent effect via formation of carbene–fluoroalkane complexes. At the RHF/3-21G level, ^{1}:CHCO$_2$Me forms bound complexes with CH$_3$F and CF$_4$ with binding energies ranging from 5.7–19.6 kcal/mol. These complexes are 1.3–1.7 times more strongly bound than complexes formed between ^{1}:CH$_2$ and the same fluoroalkanes.

Introduction

Halonium ylides or products stemming from halonium ylide intermediates have been observed in reactions of singlet carbenes with chlorine-, bromine-, and iodine-containing compounds (eq 1).[1] Although no evidence for the formation of fluoronium ylide intermediates in reactions of singlet carbenes with fluorocarbons has been reported, reversible formation of a loosely bound methylene–fluoroalkane complex has been proposed by Turro et al. to explain the apparent stabilization of singlet methylene (^{1}:CH$_2$) in a perfluoroalkane solvent.[2] Due to the rapid rate for reaction of ^{1}:CH$_2$ with hydrocarbons, intersystem crossing to the triplet state of the carbene is not observed in hydrocarbon solvents.[3] In contrast, reaction of ^{1}:CH$_2$ with fluoroalkanes is slow enough to allow intersystem crossing to occur in competition with reaction.[3] Turro et al. determined the rate for intersystem crossing from ^{1}:CH$_2$ to ^{3}:CH$_2$ in perfluorohexane solution and found it to be at least 1 order of magnitude slower than a rate extrapolated from gas-phase results. This was attributed to a decrease in spin-orbit coupling upon complexation of the singlet carbene by the fluoroalkane.



$$\mathrm{R{-}X} + {}^1{:}\mathrm{CR_2} \longrightarrow \mathrm{R{-}\overset{+}{X}{-}\overset{-}{C}R_2} \qquad (1)$$

X = Cl, Br, I

Whether or not perfluoroalkane solvent has an effect on the chemical reactivity of ^{1}:CH$_2$ has not been reported. Solvent–nitrene complexes have, however, been invoked to explain the effects of halogenated solvents on the reactivity of nitrenes.[4] Differences in product distributions between reactions in ether vs alkane solvents have also been observed for reactions of arylcarbenes,[5] silylenes,[6] and nitrenes,[7] and the solvent effects have been attributed to reversible complexation of the singlet state reactive species by ether solvent molecules.

All previous ab initio quantum chemical investigations of interactions between carbenes and fluorine-containing compounds have involved the interaction of ^{1}:CH$_2$ with HF. This system has been studied extensively at various levels of theory, from UHF/3-21G to MP4/6-311G(df,p)//MP2/6-31G(d).[8,9] At the highest level of theory applied to this system,[9] ^{1}:CH$_2$ and HF interact via a hydrogen bond to form a complex, FH–^{1}:CH$_2$, with a binding energy of approximately 10 kcal/mol relative to dissociated ^{1}:CH$_2$ and HF. No evidence for the formation of methylene fluoronium ylide, HF–^{1}:CH$_2$, was found in these studies. To our knowledge, no ab initio studies of the formation of carbene–fluoroalkane complexes have been reported.

Reasoning that complexation of a carbene by a perfluoroalkane solvent may alter its reactivity and selectivity, we have pursued additional evidence for the formation of fluoroalkane–carbene complexes through a study of the effects of perfluorohexane solvent on the selectivity of ^{1}:CH$_2$ and carbethoxycarbene (^{1}:CHCO$_2$Et) toward C–H bonds of alkane substrates. We have also investigated the interaction of ^{1}:CH$_2$ and carbomethoxycarbene (^{1}:CHCO$_2$Me) with CH$_3$F and with CF$_4$ through ab initio calculations at the RHF level with a 3-21G basis set. The results of both the experimental and theoretical studies are reported here.

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[1] (a) Ando, W. *Acc. Chem. Res.* **1977**, *10*, 179. (b) Nikolaev, V. A.; Korobitsyna, I. K. *Mendeleev Chem. J.* (*Engl. Transl.*) **1979**, *24*, 88. (c) Padwa, A.; Hornbuckle, S. F. *Chem. Rev.* **1991**, *91*, 263.

[2] Turro, N. J.; Cha, Y.; Gould, I. R. *J. Am. Chem. Soc.* **1987**, *109*, 2101.

[3] (a) Kirmse, W. *Carbene Chemistry*; Academic Press: New York, 1971. (b) Jones, M.; Moss, R. A. *Carbenes*: Wiley: New York; Vol. 1, 1972; Vol. 2, 1975.

[4] (a) Felt, G. R.; Linke, S.; Lwowski, W. *Tetrahedron Lett.* **1972**, 2037. (b) Breslow, D. S.; Edwards, E. I. *Tetrahedron Lett.* **1972**, 2041. (c) Belloli, R. C.; Whitehead, M. A.; Wollenberg, R. H.; LaBahn, V. A. *J. Org. Chem.* **1974**, *39*, 2128. (d) Tardella, P. A.; Pellacani, L. *J. Org. Chem.* **1976**, *41*, 2034.

[5] Tomioka, H.; Ozaki, Y.; Izawa, Y. *Tetrahedron* **1985**, *41*, 4987.

[6] Steele, K. P.; Weber, W. P. *J. Am. Chem. Soc.* **1980**, *102*, 6095.

[7] (a) Takeuchi, H.; Kinoshita, K.; Mohammad, A. H.; Michiharu, M.; Tsuchida, T.; Koyama, K. *J. Chem. Soc. Perkins Trans. 2* **1976**, 1201. (b) Takeuchi, H.; Kinoshita, K.; Mohammad, A. H.; Michiharu, M.; Tsuchida, T.; Koyama, K. *J. Chem. Soc. Perkins Trans. 2* **1978**, 780, 783.

[8] (a) Pople, J. A.; Raghavachari, K.; Frisch, M. J.; Binkley, J. S.; Schleyer, P.v.R. *J. Am. Chem. Soc.* **1983**, *105*, 6389. (b) Pople, J. A. *Chem. Phys. Lett.* **1986**, *132*, 144.

[9] Yates, B. F.; Bouma, W. J.; Radom, L. *J. Am. Chem. Soc.* **1987**, *109*, 2250.

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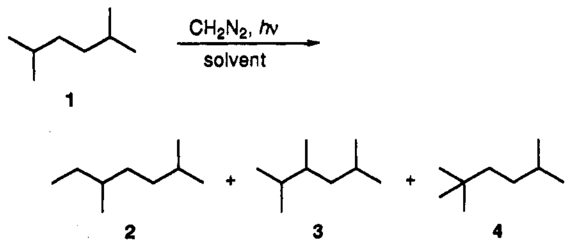
Results and Discussion

Solvent Effect Studies. The carbenes selected for study can be generated in the singlet state by direct photolysis of diazo compounds (eqs 2 and 3).[3] In hydrocarbon solution the reactions of both $^1{:}CH_2$ and $^1{:}CHCO_2Et$ are faster than intersystem crossing to the triplet ground state, permitting the study of exclusively singlet chemistry.[3,10] The product distributions from reactions run in pentane solution were compared to those from reactions run in the presence of perfluorohexane. A 1:1 solution of pentane and perfluorohexane was used as the solvent in these experiments, rather than neat perfluorohexane, in order to prevent significant intersystem crossing.

$$CH_2N_2 \xrightarrow{h\nu} {}^1{:}CH_2 + N_2 \qquad (2)$$

$$N_2CHCO_2Et \xrightarrow{h\nu} {}^1{:}CHCO_2Et + N_2 \qquad (3)$$

The reaction of $^1{:}CH_2$, generated by photolysis of CH_2N_2 (Hanovia 450-W mercury lamp, Pyrex), with 2,5-dimethylhexane (1) was examined in pentane solution and in a solution of 1:1 pentane–perfluorohexane. The CH_2N_2 was prepared by reaction of *N*-methyl-*N*-nitroso-*p*-toluenesulfonamide (Diazald) with KOH in aqueous 2-methoxyethyl ether, trapped in decalin, and the decalin solution dried over KOH pellets. The CH_2N_2 was subsequently transferred in a stream of N_2 from the decalin solution to a 10% solution of the substrate. A deficient amount of CH_2N_2 was used; typically 1–5% of the substrate underwent reaction. The carbene reacted by insertion into C–H bonds of the substrate to give products 2–4 (eq 4), as well as by insertion into the C–H bonds of the solvent to give mixtures that were analyzed by capillary GC. The distribution of products formed by reaction of $^1{:}CH_2$ with substrate 1 in pentane solution was found to be (5.22 ± 0.12)/(1.45 ± 0.02)/1.00 (2/3/4, mean value for three reactions with the error reported as the standard deviation). The per bond C–H selectivities of 1.2/0.6/1.0 (tertiary/secondary/primary) probably reflect steric hindrance to insertion at the secondary C–H bonds. These results are, within experimental error, identical to those reported by DeLuca and Neugebauer for reactions run under identical conditions ((5.18 ± 0.04)/(1.44 ± 0.01)/1.00).[11] The addition of up to 50% perfluorohexane had no detectable effect on the product distribution ((5.09 ± 0.06)/(1.41 ± 0.04)/1.00 in 1:1 pentane–perfluorohexane solution).



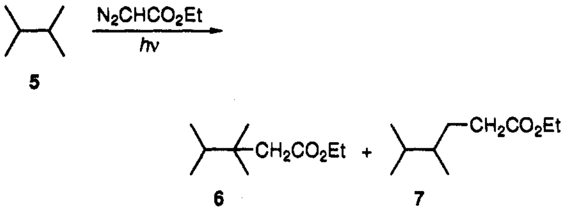
(4)

The carboethoxy substituent causes $^1{:}CHCO_2Et$ to be more selective than $^1{:}CH_2$ in reactions with alkanes.[12] The carbonyl substituent should also have a stabilizing effect on an ylide-like carbene–fluoroalkane complex through delocalization of negative charge on the carbene portion of the adduct. For these reasons, the effect of perfluorohexane solvent was also examined in reactions of $^1{:}CHCO_2Et$. The carbene was generated by direct photolysis (Hanovia 450-W mercury lamp, Pyrex) of 0.7% solutions of ethyl diazoacetate. Reaction of $^1{:}CHCO_2Et$ with 2,3-dimethylbutane (5), in which 5 served as both substrate and solvent, yielded two C–H insertion products (eq 5) which were isolated by preparative GC and identified on the basis of their NMR spectra. The product ratios were determined through GC. Photolysis of ethyl diazoacetate was also carried out in solutions of 5 (10%) in 1:1 pentane–perfluorohexane and the product ratios for the reaction of $^1{:}CHCO_2Et$ with 5 determined. The results are shown in Table 1. A small, but significant difference was observed between the product ratios determined for reactions run in different solvents. As would be expected for a stabilized carbenoid, a greater degree of selectivity was observed for the reaction run in the presence of the perfluorohexane.

Table 1. Distribution of Products from the Reaction of $^1{:}CHCO_2Et$, Generated by Photolysis of Ethyl Diazoacetate, and 5

photolysis conditions	solvent	product ratio,[a] 6/7	per bond selectivity, tertiary/primary
direct	5	0.66 ± 0.01	3.97 ± 0.04
direct	C_5H_{12}/C_6F_{14}, 1:1	0.75 ± 0.01	4.48 ± 0.09
Ph_2CO-sensitized	5	0.89 ± 0.01	5.31 ± 0.10

[a] Mean value for three reactions, determined by GC with response factors for 6 and 7 assumed equal. Errors are reported as the standard deviation.



(5)

The reaction of $:CHCO_2Et$ with 5 was also run under conditions known to produce triplet carbenes.[3,13] Ethyl diazoacetate (1%) was dissolved in a 0.2 M solution of benzophenone in 5, and the solution was irradiated at 300 nm and analyzed by GC (Table 1). The triplet carbene reacts with alkanes by a hydrogen abstraction–radical pair recombination mechanism[3] to give the same C–H insertion products produced in the reaction of the singlet carbene. The triplet carbene shows a greater preference for reaction at the tertiary C–H bond than does the singlet carbene. The enhanced selectivity observed in this reaction permits the intervention of $^3{:}CHCO_2Et$, produced by intersystem crossing in perfluorohexane solution, as a potential explanation for the observed solvent effect.

Stereospecificity Studies. The stereospecificity of the addition of $:CHCO_2Et$ to *cis*-2-pentene, as shown in Scheme 1, was used to probe the spin state of the carbene undergoing reaction in the pentane–perfluorohexane solu-

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[10] (a) Roth, H. D. *Acc. Chem. Res.* **1977**, *10*, 85. (b) Iwamura, H.; Imahashi, Y.; Kushida, K. *J. Am. Chem. Soc.* **1974**, *96*, 921.

[11] Neugebauer, S. M.; DeLuca, J. P. *Tetrahedron Lett.* **1989**, *30*, 7169.

[12] Doering, W. v E.; Knox, L. H. *J. Am. Chem. Soc.* **1961**, *83*, 1989.

[13] (a) Kopecky, K. R.; Hammond, G. S.; Leermakers, P. A. *J. Am. Chem. Soc.* **1962**, *84*, 1015. (b) Jones, M., Jr.; Ando, W.; Hendrick M. E.; Kulczycki, A., Jr.; Howley, P. M.; Hummel, K. F.; Malament, D. S. *J. Am. Chem. Soc.* **1972**, *94*, 7469. (c) Hutton, R. S.; Roth, H. D. *J. Am. Chem. Soc.* **1978**, *100*, 4324.

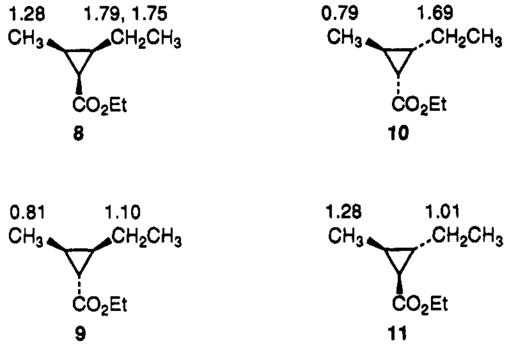
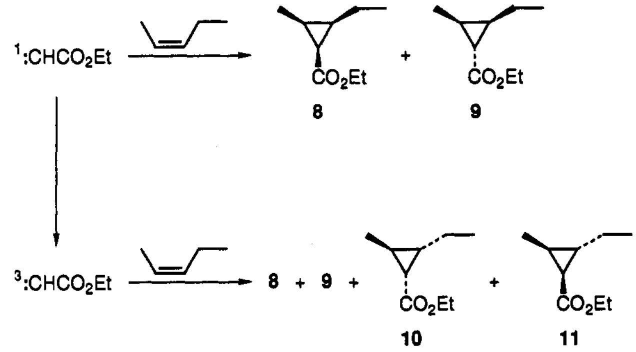


Figure 1. Chemical shifts (δ) for the ^{1}H NMR signals of the indicated methyl and methylene groups of cyclopropanes 8–11.

Scheme 1



tion. Singlet carbenes undergo stereospecific addition to double bonds, while triplet carbenes add to double bonds in a stepwise manner to give cyclopropanes in which the configuration of the starting alkene has not necessarily been preserved.[3,14] Samples of the four possible cyclopropane diastereomers were produced by stereospecific copper(II) sulfate-catalyzed reaction of ethyl diazoacetate with *cis*- and with *trans*-2-pentene for comparison with photolysis mixtures. The assignment of stereochemical configuration for the two cyclopropanes isolated from the reaction with *cis*-2-pentene (**8** and **9**) rests on the mode of preparation (methyl and ethyl substituents cis to one another) and the coupling constant for the triplet due to the proton α to the carbonyl group (8.7 Hz for isomer **8** verses 4.3 Hz for isomer **9**).[15] The signals for the ring methyl substituent and for the methylene group of the ring ethyl substituent are shifted downfield in the spectrum of **8** relative to the corresponding signals in the spectrum of **9**, probably due to through-space interaction with the ester group. Complete assignment of stereochemistry for cyclopropanes **10** and **11** isolated from the reaction with *trans*-2-pentene is based on the assumption of similar shifts in the signals for alkyl substituents cis to the ester group (Figure 1).

Cyclopropanes were the major products from the photolysis of ethyl diazoacetate in neat alkene solutions, accounting for 78% of the products in the reaction of the carbene with *cis*-2-pentene and 72% of the products in the reaction with *trans*-2-pentene. Several additional products were formed in the photolysis of each of the alkenes with ethyl diazoacetate. Although no attempt was made to assign specific structures to these products, their IR and mass spectra are consistent with the anticipated products of carbene C–H insertion and Wolff rearrangement followed by addition of the resulting ketene to the alkene.

Table 2. Stereochemistry of Cyclopropane Formation in the Reaction of ^{1}:CHCO$_2$Et, Generated by Photolysis of Ethyl Diazoacetate, and *cis*-2-Pentene[a]

photolysis conditions, solvent	product distribution[b] 8	9	10 + 11	stereospecific component[c]
direct, C_5H_{12}	0.67 ± 0.01	1.00	0.15 ± 0.01	0.92
direct, C_5H_{12}:C_6F_{14}, 1:1	0.63 ± 0.03	1.00	0.13 ± 0.01	0.93
Ph_2CO-sensitized, neat	0.17 ± 0.01	1.00	3.2 ± 0.1	0.27

[a] Starting material contains 3% *trans*-2-pentene as an impurity. [b] Mean values from at least three GC injections with response factors for stereoisomers assumed equal. Errors are reported as the standard deviation. [c] No correction for the *trans*-2-pentene impurity has been made; stereospecific component calculated as (**8** + **9**)/(**8** + **9** + **10** + **11**).

The photolysis of ethyl diazoacetate with *cis*-2-pentene was carried out in pentane solution, in 1:1 pentane–perfluorohexane solution, and in neat *cis*-2-pentene with benzophenone as triplet sensitizer. The results are shown in Table 2. In the triplet-sensitized photolysis, the configuration of the starting material was preserved in only 27% of the product, consistent with a biradical reaction intermediate. No C–H insertion products were detected. In contrast, direct photolysis produced only small amounts of cyclopropanes **10** and **11** in pentane solution, with no detectable increase in the formation of these stereoisomers in pentane–perfluorohexane solution. There was no difference between the ratios of cyclopropanes to other (presumably C–H insertion) products formed upon direct photolysis in pentane versus 1:1 pentane–perfluorohexane solution. Thus, there is no evidence to suggest that intersystem crossing to the triplet carbene occurs in 1:1 pentane–perfluorohexane solution, but not in pentane solution.

The appearance of the "wrong" isomers during the direct photolysis in alkane solution was unexpected and deserves additional comment. The *cis*-2-pentene used in these experiments contained 3% *trans*-2-pentene as an impurity, accounting for a fraction of **10** and **11** formed during the direct photolysis. Preferential reaction with the contaminating isomer was considered as a source of the remaining nonstereospecific component; however, too much of the "wrong" isomer (over 2.8%) was also seen when the reaction was carried out with *trans*-2-pentene containing 1% *cis*-2-pentene. Isomerizations of the starting alkene or the cyclopropane products during photolysis or GC analysis, as well as thermal reaction of the alkene with ethyl diazoacetate on the time-scale of the photolysis, were also ruled out through control experiments.

Although it has been generally accepted that addition of :CHCO$_2$R to alkenes is stereospecific when the carbene is generated by direct photolysis of alkyl diazoacetate,[3] a nonstereospecific reaction component has been observed in at least one other study. Jones et al. report that direct photolysis of methyl diazoacetate in *cis*-2-butene yielded 4% *trans*-cyclopropane, and reaction with *trans*-2-butene yielded 7% *cis*-cyclopropane.[13b] They suggest that the nonstereospecific component may result from addition of photoexcited alkyl diazoacetate to the alkene to form an intermediate that subsequently loses N$_2$ and closes to a cyclopropane. A similar process may be occurring in the direct photolysis of *cis*-2-pentene with ethyl diazoacetate.

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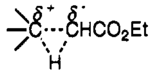
(14) Woodworth, R. C.; Skell, P. S. *J. Am. Chem. Soc.* **1959**, *81*, 3383.

(15) Pretsch, E.; Clerc, T.; Seibl, J.; Simon, W. *Spectral Data for Structure Determination of Organic Compounds*; Springer-Verlag: New York, 1983.

Regardless of the origin of the nonstereospecific reaction component, the results of these experiments do not implicate intersystem crossing from the singlet to the triplet carbene as an explanation for the observed change in the selectivity of ^{1}:CHCO$_2$Et in the presence of perfluorohexane. The conclusion based on experiments with an alkene substrate cannot, however, be extrapolated to those involving alkane substrate **5** with complete confidence. Although the rates of C–H insertion vs addition to a double bond by ^{1}:CHCO$_2$Et are comparable and products of both processes are formed in the reaction with *cis*-2-pentene, addition to a double bond is the faster reaction and accounts for approximately 80% of the product. In reactions of alkane substrate **5**, where the carbene is expected to have a slightly longer lifetime, intersystem crossing cannot be entirely ruled out and remains a possible (even though unlikely) explanation for the observed solvent effect. (Using the product ratios from the benzophenone-sensitized photolysis and from the direct photolysis in neat alkane as standards for triplet and singlet reactivity, respectively, we estimate that 38% of the product in pentane–perfluorohexane solution would have to stem from ^{3}:CHCO$_2$Et to explain the observed solvent effect.)

We have given serious consideration to two other explanations for the observed solvent effect. The first explanation depends on the polar nature of the transition state for insertion of ^{1}:CHCO$_2$Et into a C–H bond (structure **12**).[16] Because of the nonpolar character and the extremely low polarizability of perfluoroalkanes,[17] these solvents are probably less able to solvate polar transition states than even an alkane solvent. Due to the decreased solvation, the effect of alkyl substitution at the reaction site may be more pronounced in perfluorohexane solution than in alkane solution, leading to enhanced selectivity. This would be analogous to the greater importance of substituent effects seen for gas-phase reactions vs reactions in solution.[18] The second explanation involves the modification of the selectivity of ^{1}:CHCO$_2$Et through formation of carbene–fluoroalkane complexes such as those proposed by Turro et al.[2]



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Ab Initio Studies of Carbene–Fluoroalkane Interactions. In order to investigate the formation of complexes between singlet carbenes and fluoroalkane solvents, we have performed ab initio geometry optimizations on two different carbenes, ^{1}:CH$_2$ and ^{1}:CHCO$_2$Me, interacting with two different fluoroalkanes, CH$_3$F and CF$_4$. We expect that the interaction of ^{1}:CHCO$_2$Me with the fluoroalkanes will be similar to the carbene studied experimentally, ^{1}:CHCO$_2$Et.

The ab initio calculations reported here were carried out at the RHF level using a standard 3-21G basis set and the GAMESS program.[19] Further calculations employing larger basis sets and electron correlation are also in progress. We expect, however, on the basis of previous theoretical studies of carbene complexes and ylides,[8,9,20] that the 3-21G basis set at the RHF level provides a reasonable qualitative description of these systems.

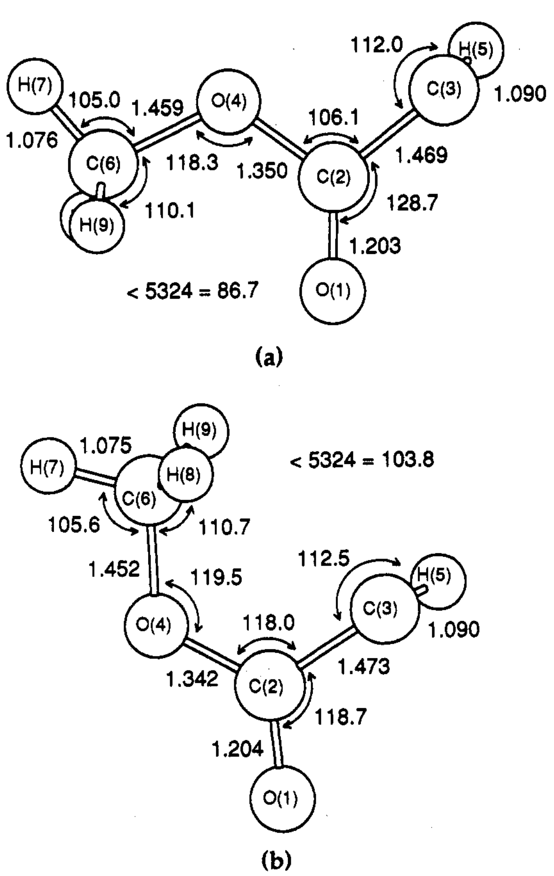

Figure 2. Optimized geometries at the RHF/3-21G level for the *s-trans-* (a) and *s-cis-*conformers (b) of ^{1}:CHCO$_2$Me.

The optimized structure of ^{1}:CHCO$_2$Me at the RHF/3-21G level is shown in Figure 2. Equilibrium bond lengths and angles are also presented in Figure 2. Both the *s-cis-* (Figure 2a) and *s-trans-*conformations (Figure 2b) are stable, with the *s-cis-*conformation lying 8.2 kcal/mol above the *s-trans* global minimum. The carbon–oxygen framework in both structures is nearly planar, with deviations of less than 8°. In the *s-trans-*conformation, the hydrogen (H5) attached to the carbene center (C3) is rotated out of the plane of the carbon–oxygen framework by 87°. In the *s-cis-*conformation, the angle is 104°. The out-of-plane orientation of the H attached to the carbene center is similar to that seen in other carbenes containing carbonyl groups adjacent to the carbene center. Though unstable to rearrangement to ketene at higher levels of theory, the H attached to the carbene center in formylcarbene is rotated out of the plane by 85° at the SCF/DZ+P level.[21] In addition, acetylcarbene is calculated to be nonplanar at the carbene center by 87° at the MP4/6-31G*//6-31G* level.[22] The barrier to rotation for the CH group in the

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(16) (a) Doering, W. v. E.; Knox, L. H. *J. Am. Chem. Soc.* **1961**, *83*, 1989. (b) Sauers, R. R.; Kiesel, R. J. *J. Am. Chem. Soc.* **1967**, *89*, 4695.

(17) Sheppard, W. A.; Sharts, C. M. *Organic Fluorine Chemistry*; W. A. Benjamin: New York, 1969; pp 40–43.

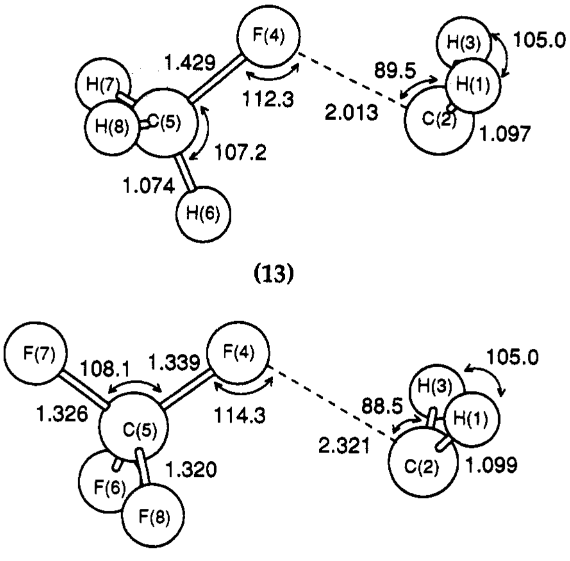
(18) Taft, R. W. *Prog. Phys. Org. Chem.* **1983**, *14*, 247.

(19) (a) Schmidt, M. W.; Baldridge, K. K.; Boatz, J. A.; Jensen, J. H.; Koseki, S.; Gordon, M. S.; Nguyen, K. A.; Windus, T. L.; Elbert, S. T. *QCPE Bull.* **1990**, *10*, 52. (b) Schmidt, M. W.; Baldridge, K. K.; Boatz, J. A.; Elbert, S. T.; Gordon, M. S.; Jensen, J. H.; Koseki, S.; Matsunaga, N.; Nguyen, K. A.; Shujun, S; Windus, T.L.; Dupuis, M.; Montgomery, J. A. *J. Comput. Chem.* **1993**, *11*, 1347.

(20) Eades, R. A.; Gassman, P. G.; Dixon, D. A. *J. Am. Chem. Soc.* **1981**, *103*, 1066.

(21) Tanaka, K.; Yoshimine, M. *J. Am. Chem. Soc.* **1980**, *102*, 7655.

(22) Turecek, F.; Drinkwater, D. E.; McLafferty, F. W. *J. Am. Chem. Soc.* **1991**, *113*, 5958.



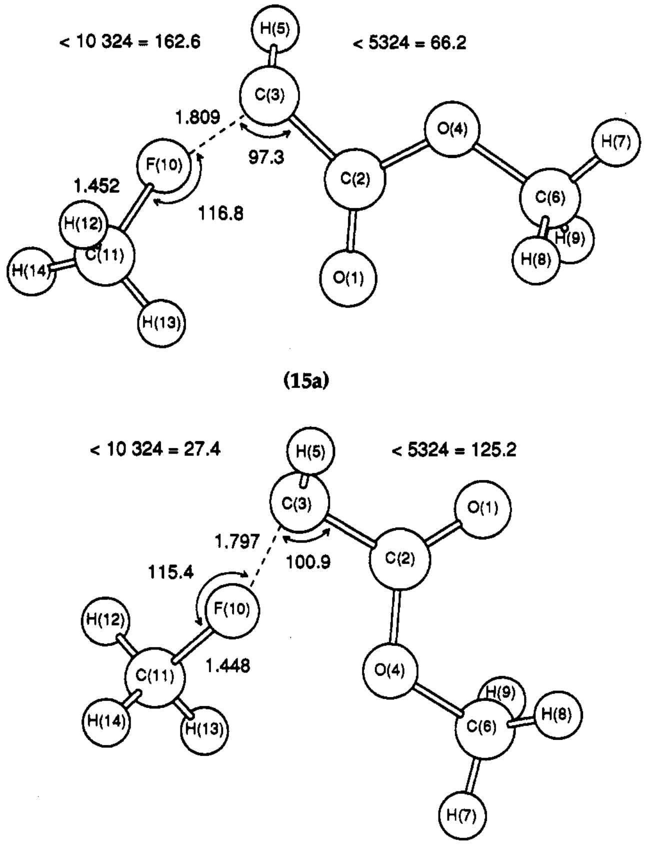
(13)

(14)

Figure 3. Optimized geometries at the RHF/3-21G level for the complexes of ^{1}:CH$_2$ with CH$_3$F (**13**) and CF$_4$ (**14**).

s-trans-conformation, which passes through a nearly linear C3–C2–H5 transition state, was calculated to be 15.2 kcal/mol.

At the RHF/3-21G level, we find that ^{1}:CH$_2$ and ^{1}:CHCO$_2$Me form bound complexes with both of the fluoroalkanes. All of the structures for the ^{1}:CH$_2$ and ^{1}:CHCO$_2$Me complexes formed with fluoroalkanes reported below have been verified to be minima on their potential energy surfaces by determination of the vibrational frequencies at the optimized geometries. Equilibrium structures for the CH$_3$F–^{1}:CH$_2$ complex (**13**) and the CF$_4$–^{1}:CH$_2$ complex (**14**) are shown in Figure 3. Unlike the previous ab initio studies which predict the formation of a FH–^{1}:CH$_2$ hydrogen-bonded complex,[8,9] we have searched for but found no evidence of the existence of a stable hydrogen-bonded FCH$_3$–^{1}:CH$_2$ complex. It was found that two different stable conformations exist for the complexes formed between *s-trans*-^{1}:CHCO$_2$Me and each of the fluoroalkanes. The structures of the CH$_3$F complexes **15a,b** are shown in Figure 4, and those of the CF$_4$ complexes **16a,b** are presented in Figure 5. Equilibrium bond lengths and angles are also listed in Figures 3–5. In one set of conformations of the ^{1}:CHCO$_2$Me complexes, the carbonyl group of the carbene is directed toward the fluoroalkane (**15a** and **16a**). In the second set of conformations, the oxygen of the carbene methoxy group is directed toward the fluoroalkane (**15b** and **16b**). In the CH$_3$F–^{1}:CHCO$_2$Me complexes **15a** and **15b**, the separation of 2.32–2.37 Å between H13 of CH$_3$F and the carbonyl oxygen (O1) in the case of **15a**, or the methoxy oxygen (O4) in the case of **15b**, indicates the possibility of a weak hydrogen-bonding interaction.



(15a)

(15b)

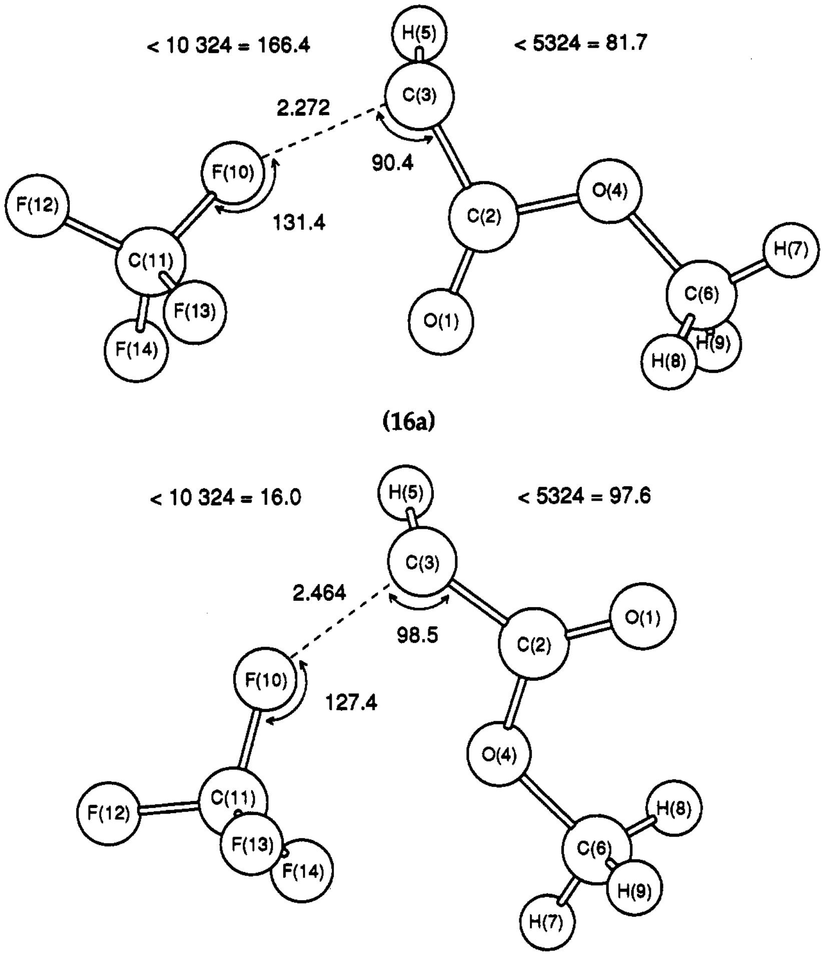
Figure 4. Optimized geometries at the RHF/3-21G level for the two conformations of the complex formed between *s-trans*-^{1}:CHCO$_2$Me and CH$_3$F (**15a** and **15b**). The bond lengths, bond angles, and dihedral angles not reported in the figure are similar to those for the separated species. Differences in bond lengths in the complex versus the monomers are less than 0.014 Å, except for the C11–F10 distance, which is elongated by 0.048 and 0.044 Å in the two conformations (**15a** and **15b**) compared to the 1.404 Å C–F bond distance calculated for CH$_3$F at the same level of theory. Differences in bond angles are less than 10° in all cases, and differences in dihedral angles are less than 4°, except for the H5–C3–C2–O4 dihedral angle reported above.

Table 3. Binding Energies and Electron Transfer for Carbene–Fluoroalkane Complexes Calculated at the RHF/3-21G Level

system	binding energy,[a] kcal/mol	electron transfer[b]
CH$_3$F–^{1}:CH$_2$ (**13**)	12.2	0.09
CF$_4$–^{1}:CH$_2$ (**14**)	4.3	0.03
CH$_3$F–^{1}:CHCO$_2$Me (**15a**)	19.6	0.15
CH$_3$F–^{1}:CHCO$_2$Me (**15b**)	16.1	0.15
CF$_4$–^{1}:CHCO$_2$Me (**16a**)	7.1	0.04
CF$_4$–^{1}:CHCO$_2$Me (**16b**)	5.7	0.02

[a] Measured relative to the energies of the separated species determined at the RHF/3-21G level. [b] The amount of charge transferred from the fluoroalkane to the carbene based on net Mulliken populations.

Binding energies for the carbene–fluoroalkane complexes, measured relative to the separated species, are reported in Table 3. The binding energies determined for these systems range from 4.3 to 19.6 kcal/mol. The two different conformations of the CH$_3$F–^{1}:CHCO$_2$Me complexes differ in energy by 3.5 kcal/mol, while the two CF$_4$–^{1}:CHCO$_2$Me complexes differ by only 1.4 kcal/mol. The complexes which have the carbonyl pointing in the direction of the fluoroalkane (**15a** and **16a**) are slightly more stable. The CH$_3$F–^{1}:CHCO$_2$Me complexes (**15a** and **15b**) exhibit enhanced stabilization relative to the CF$_4$ complexes, possibly due to the weak hydrogen bonding interaction discussed above, but also by stronger dipolar interactions. The results reported in Table 3 clearly show that the binding energies for the ^{1}:CH$_2$ complexes are smaller than those reported for the respective ^{1}:CHCO$_2$Me complexes. These differences are significant. The complexes formed with ^{1}:CHCO$_2$Me are 1.3–1.7 times more strongly bound than the respective ^{1}:CH$_2$ complexes.



(16a)

(16b)

Figure 5. Optimized geometries at the RHF/3-21G level for the two conformations of the complex formed between *s-trans*-^{1}:CHCO$_2$Me and CF$_4$ (**16a** and **16b**). The bond lengths, bond angles, and dihedral angles not reported in the figure are similar to those calculated for the separated species. Differences in bond lengths in the complex versus the monomers are less than 0.009 Å in all cases, differences in bond angles are less than 5°, and differences in dihedral angles are less than 3°, except for the H5–C3–C2–O4 dihedral angle reported in the figure.

We have also examined the amount of electron transfer from the fluoroalkane to the carbene in each complex, based on Mulliken population analysis. Table 3 gives the calculated total electron transfer for each system. In the complexes formed between ^{1}:CH$_2$ or ^{1}:CHCO$_2$Me and CF$_4$, the electron transfer is small, around 0.02–0.04. The electron transfer in the complexes formed between ^{1}:CH$_2$ or ^{1}:CHCO$_2$Me and CH$_3$F is larger, around 0.09–0.15. This correlates with the stronger binding energies of the CH$_3$F complexes versus the CF$_4$ complexes. The structure, energetics (19 kcal/mol binding energy), and charge transfer (0.16) calculated for ^{1}:CH$_2$ interacting with H$_2$O[9,23] are similar to those for the more strongly bound carbene–fluoroalkane systems studied here.

Conclusions

We have found that :CHCO$_2$Et, produced by direct photolysis of ethyl diazoacetate, is more selective in its reactions with the C–H bonds of alkane substrates in the presence of perfluorohexane solvent. Experiments in which the stereochemistry of carbene addition to *cis*-2-pentene was used to probe the carbene spin state suggest that intersystem crossing does not occur in the 1:1 pentane–perfluorohexane solutions used in the solvent effect studies. The observed change in selectivity is most likely due to the effect of the solvent upon the reactions of ^{1}:CHCO$_2$Et. The effect may be due to differences in the solvating abilities of perfluorohexane vs an alkane toward the transition state for the insertion reactions, or due to complexation of ^{1}:CHCO$_2$Et by perfluorohexane to form a carbenoid intermediate with modified selectivity, or a combination of the two effects. Ab initio calculations at the RHF/3-21G level support the formation of weakly bound complexes between carbenes and fluoroalkanes. The interaction between ^{1}:CHCO$_2$Me and the fluoroalkanes studied theoretically, CH$_3$F and CF$_4$, was significantly stronger than the interaction between ^{1}:CH$_2$ and the same fluoroalkanes, indicating that any solvent effect should be more pronounced for a carboalkoxycarbene than for methylene, in agreement with the experimental results.

Experimental Section

General Remarks. Infrared spectra were obtained with a Nicolet 5SXC FTIR interfaced with a Hewlett-Packard 5890 GC fitted with a Hewlett Packard HP-5 column (25 m × 0.32 mm, 1.05 mm film thickness). ^{1}H and ^{13}C NMR spectra were recorded on a Varian Gemini spectrometer operating at 300 and 75.5 MHz,

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[23] Moreno, M.; Lluch, A. O.; Bertran, J. *Can. J. Chem.* **1987**, *65*, 2774.

respectively, and referenced to the solvent peak. Mass spectra were obtained on a Hewlett-Packard 5790 Series quadrupole mass detector interfaced with a Hewlett-Packard 5890 GC fitted with an Alltech RSL-150 column, 30 m × 0.25 mm, 0.25-mm film thickness. Preparative GC was carried out with a Gow-Mac Series 580 GC fitted with a 20% Carbowax 20M on Chromasorb W column (2 m × 3 mm). Most capillary GC analyses were performed on a Hewlett-Packard 5890 GC with FID. The following columns were used: SGE BPX5, 25 m × 0.22 mm, 0.25-mm film thickness (col A), Supelcowax 10, 30 m × 0.20 mm, 0.20-mm film thickness (col B), Supelco SPB-1701, 30 m × 0.25 mm, 0.25-mm film thickness (col C), Alltech Econocap SE-30, 30 m × 0.25 mm, 0.25-mm film thickness (col D). GC response factors for stereoisomers were assumed identical. Samples of *cis*- and *trans*-2-pentene were analyzed using a Hewlett-Packard 5970 mass-selective detector interfaced with a Hewlett-Packard 5890 GC fitted with a J&W DB-624 megabore column, 75 m × 0.53 mm, 0.25-mm film thickness; the sample was injected on column via a Tekmar ALS 2000 purge and trap.

The procedure for the preparation of solutions of CH_2N_2 in decalin has been described elsewhere.[24] Pentane and all substrates were filtered through alumina and distilled from Na under N_2 prior to use. *cis*-2-Pentene was purchased from TCI and contained 3% *trans*-2-pentene. *trans*-2-Pentene was purchased from Fluka and contained 1% *cis*-2-pentene.

Photolysis of CH_2N_2 Solutions. (*Warning!* All operations involving CH_2N_2 should be carried out in an efficient fume hood and behind a safety shield.) The CH_2N_2 was transferred in a stream of N_2 from a decalin solution to N_2-purged solutions of substrate (1.5 mL) and solvent (13.5 mL) in a Pyrex vessel. The solutions were cooled by contact with a tap water-cooled cold finger and irradiated 45 min with a Hanovia 450-W mercury lamp held in a water-cooled Pyrex sleeve. Reaction mixtures were analyzed by GC on col A.

Direct Photolysis of Ethyl Diazoacetate Solutions. Solutions of ethyl diazoacetate (0.10 mL) and substrate (1.5 mL) in solvent (13.5 mL) were placed in a Pyrex vessel, purged with N_2, and irradiated 3 h with a Hanovia 450-W mercury lamp held in a water-cooled Pyrex sleeve. During irradiation the solutions were cooled by contact with a tap water-cooled cold finger. Reaction mixtures were analyzed by GC (substrate, col): 2,3-dimethylbutane, col B; *cis*-2-pentene, col C and D; *trans*-2-pentene, col C and D.

Triplet-Sensitized Photolysis of Ethyl Diazoacetate Solutions. Solutions of ethyl diazoacetate (0.02 mL) and benzophenone (0.08 g) in substrate (2 mL) were placed in a quartz tube fitted with a water-cooled condenser and irradiated, under N_2, for 3 h using a Rayonet reactor and 300-nm lamps. Reaction mixtures were analyzed by GC on col C.

Isolation of Products from the Direct Photolysis of Ethyl Diazoacetate in 2,3-Dimethylbutane. A solution of ethyl diazoacetate (0.10 mL) in 2,3-dimethylbutane (10 mL) was irradiated as described above. Removal of unreacted 2,3-dimethylbutane by distillation gave an oil that was separated into two components by preparative GC (120 °C).

Spectral data for ethyl 3,3,4-trimethylpentanoate (**6**), shown by GC (col B) to be of 99% purity: ^{1}H NMR ($CDCl_3$) δ 4.09 (q, 2H), 2.18 (s, 2H), 1.57 (hept, 1H), 1.24 (t, 3H), 0.93 (s, 6H), 0.85 (d, 6H); ^{13}C NMR ($CDCl_3$) 172.8, 59.8, 44.5, 36.5, 35.8, 24.2, 17.4, 14.3 ppm; MS, *m/e* (rel inten) 127 (15), 88 (30), 87 (53), 85 (50), 43 (100).

Spectral data for ethyl 4,5-dimethylhexanoate (**7**), shown by GC (col B) to be of 99% purity: ^{1}H NMR ($CDCl_3$) δ 4.10 (q, 2H), 2.27 (m, 2H), 1.67 (m, 1H), 1.56 (m, 1H), 1.39 (m, 1H), 1.3 (m, 1H), 1.23 (t, 3H), 0.85 (d, 3H), 0.80 (d, 3H), 0.79 (d, 3H); ^{13}C NMR ($CDCl_3$) 174.1, 60.1, 38.2, 32.6, 31.9, 29.2, 20.1, 18.0, 15.0, 14.2 ppm; MS, *m/e* (rel inten) 129 (19), 127 (7), 101 (75), 88 (58), 83 (45), 43 (100).

$CuSO_4$-Catalyzed Reaction of Ethyl Diazoacetate and *cis*-2-Pentene. A solution of ethyl diazoacetate (2.5 g, 0.022 mol) in pentane (2.3 mL) was added dropwise to a stirred refluxing mixture of anhydrous $CuSO_4$ (0.13 g) and *cis*-2-pentene (1.5 g, 0.021 mol) and the mixture was refluxed 2.5 h. The mixture was filtered through alumina and the solvent and unreacted alkene were removed from the filtrate by distillation. Evaporative distillation of the residue at reduced pressure produced a colorless oil (0.80 g) containing diethyl 2-butenedioate (67% of mixture) and ethyl 2-ethyl-3-methylcyclopropanecarboxylates **8** and **9** (10 and 23% of mixture, 8% of theory). Cyclopropanes **8** and **9** were isolated by preparative GC (95 °C).

Spectral data for **8**, shown by GC (col B) to be of 99.2% purity with 0.8% **9** as impurity: ^{1}H NMR (C_6D_6) δ 3.99 (m, 2H), 1.79 (m, 1H), 1.75 (m, 1H), 1.57 (t, 1H, J = 8.7 Hz, C*H*CO_2Et), 1.28 (d, 3H), 1.06 (m, 1H), 0.98 (t, 3H), 0.93 (t, 3H), 0.9 (m, 1H); ^{13}C NMR (C_6D_6) 171.5, 59.2, 26.9, 20.6, 18.9, 15.6, 14.4, 14.1, 7.3 ppm; IR (gas phase) 1740, 1156 cm^{-1}; MS, *m/e* (rel inten) 156 (7, M$^+$), 141 (31), 127 (19), 113 (21), 111 (24), 99 (25), 83 (23), 82 (34), 69 (44), 67 (29), 55 (100), 53 (25), 43 (35), 41 (77), 39 (58).

Spectral data for **9**, shown by GC (col B) to be of 97.3% purity with 2.0% **8** as impurity: ^{1}H NMR (C_6D_6) δ 4.00 (q, 2H), 1.57 (m, 1H), 1.50 (m, 1H), 1.10 (m, 2H), 1.04 (t, 1H, J = 4.3 Hz, C*H*CO_2-Et), 0.98 (t, 3H), 0.82 (t, 3H), 0.81 (d, 3H); ^{13}C NMR (C_6D_6) 173.6, 59.8, 29.3, 27.6, 21.5, 20.4, 14.1, 13.7, 11.4 ppm; IR (gas phase) 1743, 1175 cm^{-1}; MS, *m/e* (rel inten) 156 (2, M$^+$), 141 (33), 127 (23), 111 (33), 99 (22), 83 (23), 81 (28), 69 (48), 55 (100), 53 (27), 43 (28), 41 (68), 39 (53).

$CuSO_4$-Catalyzed Reaction of Ethyl Diazoacetate and *trans*-2-Pentene. The procedure described above was repeated using *trans*-2-pentene. The resulting colorless oil (0.77 g) contained diethyl 2-butenedioate (83% of mixture) and cyclopropanes **10** and **11** (17% of mixture, 4% of theory). Cyclopropanes **10** and **11** were isolated by preparative GC (95 °C).

Spectral data for **10**, shown by GC (col A) to be of 89% purity with 11% of **11** as impurity: ^{1}H NMR (C_6D_6) δ 4.01 (m, 2 H), 1.69 (m, 2 H), 1.38 (m, 2 H), 0.99 (t, 3 H), 0.90 (t, 3 H), 0.79 (d, 3 H), 0.71 (m, 1 H); ^{13}C NMR (C_6D_6) 172.2, 59.9, 32.6, 26.5, 22.1, 20.3, 17.9, 14.4, 14.0 ppm; IR (gas phase) 1741, 1170 cm^{-1}; MS, *m/e* (rel inten) 141 (51), 113 (38), 111(38), 99 (31), 95 (28), 87 (26), 82 (27), 69 (63), 67 (28), 55 (100), 53 (27), 43 (37), 41 (84), 39 (63).

Spectral data for **11**, shown by GC (col A) to be of 97% purity with 3% of **10** as impurity: ^{1}H NMR (C_6D_6) δ 4.01 (q, 2 H), 1.41 (d of d, 1 H), 1.33 (m, 1 H), 1.28 (d, 3 H), 1.01 (m, 2 H), 0.99 (t, 3 H), 0.8 (m, 1 H), 0.77 (t, 3 H); ^{13}C NMR (C_6D_6) 171.6, 59.9, 30.6, 26.3, 25.7, 23.3, 14.4, 13.1, 12.2 ppm; IR (gas phase) 1742, 1173 cm^{-1}; MS, *m/e* (rel inten) 141 (53), 127 (37), 113 (28), 111 (35), 99 (42), 69 (47), 67 (22), 55 (100), 53 (26), 43 (35), 41 (70), 39 (58).

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Supplementary Material Available: ^{1}H NMR spectra for **6**–**11** (6 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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[24] Young, T. A.; O'Rourke, C.; Gray, N. B.; Lewis, B. D.; Dvorak, C. A. Kuen, S. K. DeLuca, J. P. *J. Org. Chem.* **1993**, *58*, 6224.