acetone solution. Structures of both **2** and **4**, determined by X-ray diffraction, are nearly identical except for the geometries of the C_2H_2 ligands.

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Supplementary Material Available: Tables of positional parameters and equivalent *B* values, anisotropic displacement parameters, complete bond distances and bond angles, least-squares planes, and torsion angles (12 pages); experimental and calculated structure factors for the structures of **2** and **4** (26 pages). Ordering information is available on any current masthead page.

Thermal Reactions of Substituted Cyclopropenone Acetals. Regio- and Stereochemistry of Vinylcarbene Formation and Low-Temperature [3 + 2] Cycloaddition†

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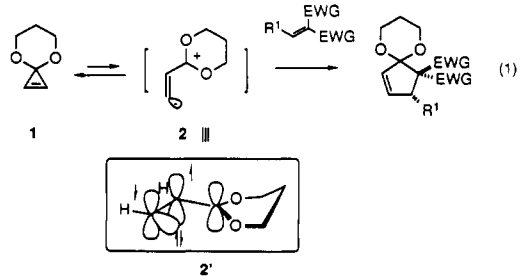
Abstract: Cyclopropenone acetals bearing olefinic substituents of diverse electronic character have been synthesized and examined for their thermal behavior toward water and electron-deficient olefins. The substituted cyclopropenes underwent regio- and stereoselective hydration to give acrylate derivatives via vinylcarbene species, providing new data on the regio- and stereochemistry of vinylcarbene species. They also underwent regioselective [3 + 2] cycloadditions to electron-deficient olefins to give a variety of cyclopentenone acetals. In particular, phenylthio and ester substituents connected to the cyclopropene carbon effected highly regioselective vinylcarbene formation below room temperature to permit the thermal [3 + 2] cycloaddition to take place under extremely mild conditions.

Reversible generation and thermal [3 + 2] cycloaddition of the singlet vinylcarbene **2** under mild thermal conditions (70–80 °C) is an extremely unique reaction (eq 1).[1] Boger's extensive synthetic and mechanistic studies have revealed some useful and unusual characteristics of the reaction.[2] Synthetically, the reaction in eq 1 represents one of a few all-carbon thermal [3 + 2] cycloaddition reactions[3] that is synthetically viable for the preparation of five-membered carbocycles and may serve as a complement to the Diels–Alder reaction. Among the various types of reactions available to vinylcarbenes,[4] Boger's cycloaddition reaction (eq 1) represents the only example of the [3 + 2] cycloaddition of vinylcarbene species.[5] Typical thermal reactions of vinylcarbenes include intramolecular rearrangement (e.g., CH insertion)[6] or ring closure to cyclopropenes and occasional participation in [1 + 2] cycloaddition reactions.[7,8] The ab initio calculations with electron correlation[2a] indicate that the carbene **2** is most stable in its planar closed-shell singlet, π-delocalized form **2'**, which is consistent with the experimental behavior of the intermediates.



Although the cycloaddition of **1** is a synthetically powerful and mechanistically stimulating reaction, further extension of the chemistry beyond the currently established level has been difficult owing to the lack of substituted derivatives of **1**. This situation has recently changed, as a variety of cyclopropenone acetals **5** and **7** are now available by the reaction of stable metal salts **4** and **6**[9] with electrophiles (eq 2).[10] The neopentyl glycol acetals **3**,

† Dedicated to Professor Gilbert Stork on the occasion of his 70th birthday.

(1) Albert, R. M.; Butler, G. B. *J. Org. Chem.* **1977**, *42*, 674.

(2) (a) Review: Boger, D. L.; Brotherton, C. E. *Advances in Cycloaddition*; Curran, D. P., Ed.; JAI Press: Greenwich, CT, 1990; Vol. 2, p 147. (b) Boger, D. L.; Brotherton, C. E. *J. Am. Chem. Soc.* **1986**, *108*, 6695. (c) Boger, D. L.; Wysocki, R. J., Jr. *J. Org. Chem.* **1988**, *53*, 3408.

(3) (a) For 1,3-dipolar cycloadditions in the five-membered heterocycle synthesis, see: Huisgen, R. *1,3-Dipolar Cycloaddition Chemistry*; Padwa, A., Ed.; Wiley-Interscience: New York, 1984. (b) Trimethylenemethane chemistry in thermal [3 + 2] cycloaddition: Berson, J. A.; McDaniel, D. M.; Corwin, L. R.; Davis, J. H. *J. Am. Chem. Soc.* **1972**, *94*, 5508. Berson, J. A.; McDaniel, D. M.; Corwin, L. R. *J. Am. Chem. Soc.* **1972**, *94*, 5509. (c) For our interests and other pertinent references in thermal [3 + 2] cycloaddition: Yamago, S.; Nakamura, E. *J. Am. Chem. Soc.* **1989**, *111*, 7285. Yamago, S.; Nakamura, E. *J. Org. Chem.* **1990**, *55*, 5553.

(4) Review: Baird, M. S. *Top. Curr. Chem.* **1988**, *144*, 150.

(5) It has been shown that the [3 + 2] cycloaddition is not a combined result of [1 + 2] cycloaddition and vinylcyclopropane rearrangement (ref 2a).

(6) (a) For thermal reactions: Battiste, M. A.; Halton, B.; Grubbs, R. H. *J. Chem. Soc., Chem. Commun.* **1967**, 907. Kirms, M. A.; Primke, H.; Stohlmeier, M.; de Meijere, A. *Recl. Trav. Chim. Pays-Bas* **1986**, *105*, 462. (b) Photochemical reaction: Pincock, J. A.; Moutsokapas, A. A. *Can. J. Chem.* **1977**, *55*, 979. Pincock, J. A.; Mathur, N. C. *J. Org. Chem.* **1982**, *47*, 3699. Padwa, A. *Acc. Chem. Res.* **1979**, *12*, 310. Padwa, A.; Blacklock, T. J.; Getman, D.; Hatanaka, N. *J. Am. Chem. Soc.* **1977**, *99*, 2344. Padwa, A.; Blacklock, T. J.; Getman, D.; Hatanaka, N.; Loza, R. *J. Org. Chem.* **1978**, *43*, 1481. Zimmerman, H. E.; Aasen, S. M. *J. Am. Chem. Soc.* **1977**, *99*, 2342. (c) For organometallic complexes, see: Leftin, J. H.; Gil-Av, E. *Tetrahedron Lett.* **1972**, 3367. Padwa, A.; Blacklock, T. J.; Loza, R. *J. Am. Chem. Soc.* **1981**, *103*, 2404. Vidal, M.; Vincens, M.; Arnaud, P. *Bull. Soc. Chim. Fr.* **1972**, 657.

(7) (a) Review: Binger, P.; Büch, H. M. *Top. Curr. Chem.* **1987**, *135*, 84. (b) Boger, D. L.; Brotherton, C. E. *Tetrahedron Lett.* **1984**, *25*, 5611. (c) Baird, M. S.; Buxton, S. R.; Whitley, J. S. *Tetrahedron Lett.* **1984**, 1509. (d) Weber, W.; de Meijere, A. *Chem. Ber.* **1985**, *118*, 2450.

(8) For organometallic complexes of vinylcarbenes, see: (a) Mitsudo, T.; Nakanishi, H.; Inubushi, T.; Morishima, I.; Watanabe, Y.; Takegami, Y. *J. Chem. Soc., Chem. Commun.* **1976**, 416. (b) Binger, P.; McMeeking, J.; Schäfer, H. *Chem. Ber.* **1984**, *117*, 1551. For synthetic use, see: (c) Davies, H. M. L.; Saikali, E.; Young, W. B. *J. Org. Chem.* **1991**, *56*, 5696.

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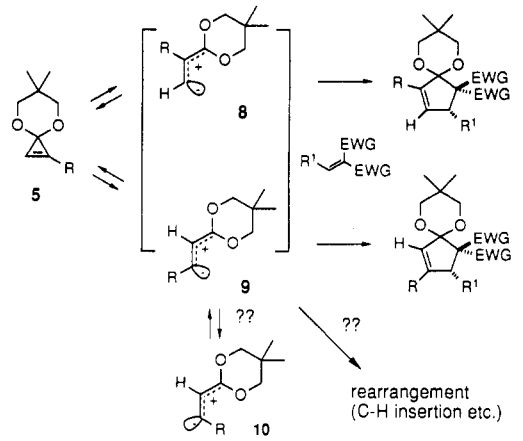
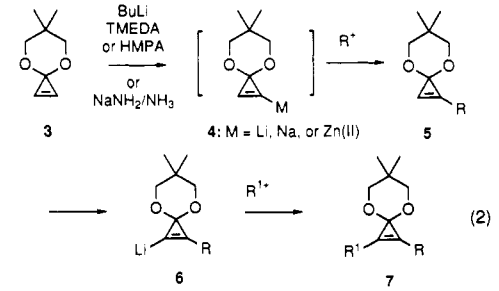
Scheme I



5, and **7** were found to be more practically useful than **1**, since the dimethyl substitution on the acetal greatly simplifies the ^1H and ^{13}C NMR spectra and gives higher yields in their preparation.[10] (In addition, neopentyl glycol is much cheaper than 1,3-propanediol.)



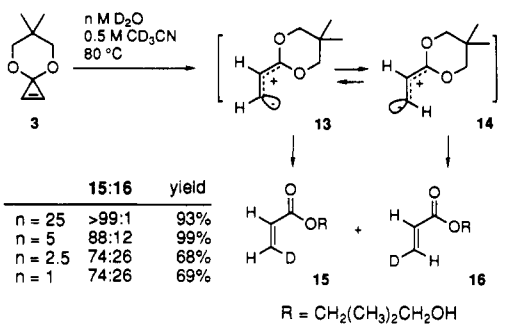
With this versatile access to substituted cyclopropanes in hand, we set out to explore the potential of the Boger [3 + 2] cycloaddition for the synthesis of highly substituted cyclopentenones. Of particular interest was the possibility that the introduction of an appropriate R or R^1 group to **7** might allow controlled formation of the vinylcarbene species. Indeed, we found that substituents had a dramatic impact on the regioselectivity of the vinylcarbene formation as well as on the overall rate of the [3 + 2] cycloaddition and that *suitably substituted cyclopropenone acetals underwent thermal [3 + 2] cycloaddition to geminally disubstituted electron-deficient olefins even at 0 °C.*

Herein we describe the synthetic studies of the [3 + 2] cycloaddition of the substituted cyclopropenone acetals as an entry to highly substituted cyclopentenone derivatives as well as the results of studies on the regio- and stereochemistry of the vinylcarbene-forming reaction.

Results

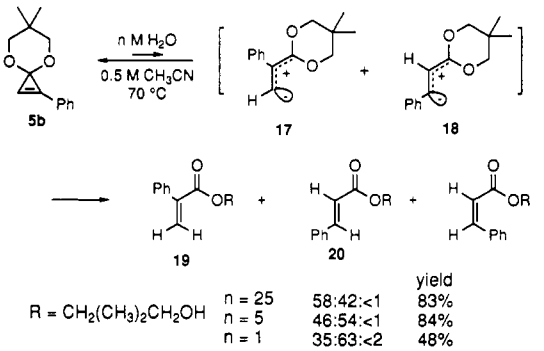
Regio- and Stereochemistry of Vinylcarbene Formation. The thermal [3 + 2] cycloaddition of the substituted cyclopropenone acetal **5** to an electron-deficient olefin (Scheme I) is more complex than that for the parent compound **1** or **3**. Substituents on the cyclopropenyl olefin create an issue of the regioselectivity of the C–C σ-bond cleavage (i.e., the formation of **8** or **9**). The reversible nature of the carbene formation[2] requires that the equilibration between the regioisomers **8** and **9**, the relative rate of the cycloaddition of each isomer, and the stereochemistry of the vinylcarbenes[11] (i.e., **9** vs **10**) be considered. Another consideration

Scheme II



	15:16	yield
n = 25	>99:1	93%
n = 5	88:12	99%
n = 2.5	74:26	68%
n = 1	74:26	69%

Scheme III

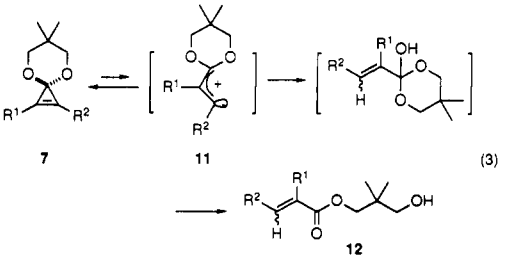


			yield
R = $CH_2(CH_3)_2CH_2OH$	n = 25	58:42:<1	83%
	n = 5	46:54:<1	84%
	n = 1	35:63:<2	48%

is that the carbene species might undergo intramolecular rearrangement, the most commonly observed reaction of vinylcarbenes,[12] before the intermolecular [3 + 2] cycloaddition.

Electronic and steric factors are expected to influence the rate and the stability of the isomeric π-delocalized vinylcarbene species **8** and **9**. In light of the electronic structure **2'**,[2a] an anion-stabilizing substituent R may facilitate the formation and enhance the stability of isomer **9** over **8**. Isomer **8** may suffer steric destabilization due to the acetal moiety occupying the symmetry plane of the delocalized carbene. In order to gain initial insights on the contribution of these factors, we investigated four typical cyclopropenone acetals: the parent compound **3** and the ethyl (**5a**, R = Et), phenyl (**5b**, R = Ph), and trimethylsilyl (**5c**, R = Me_3Si) substituted compounds.

In initial studies, we first determined the regioselectivity of the cyclopropene ring cleavage under the conditions where the vinylcarbene might be kinetically trapped as it is formed. Boger[2b] has shown that the parent vinylcarbene **2** undergoes smooth intermolecular insertion into the O–H bond of methanol.[13] Thus, we conjectured that a high concentration of water would rapidly quench the carbene **11** (prior to equilibration of the carbene isomers) to give the acrylate ester **12** (eq 3).[14]



Thus, we examined the behavior of the parent compound **3** in aqueous media in detail (Scheme II). The reaction of **3** in a 25 M solution of D_2O (50 equiv of **3**) proceeded quantitatively with

(9) Isaka, M.; Matsuzawa, S.; Yamago, S.; Ejiri, S.; Miyachi, Y.; Nakamura, E. *J. Org. Chem.* **1989**, *54*, 4727.

(10) (a) Isaka, M.; Ando, R.; Morinaka, Y.; Nakamura, E. *Tetrahedron Lett.* **1991**, *32*, 1339. (b) Isaka, M.; Ejiri, S.; Nakamura, E. *Tetrahedron* **1992**, *48*, 2045.

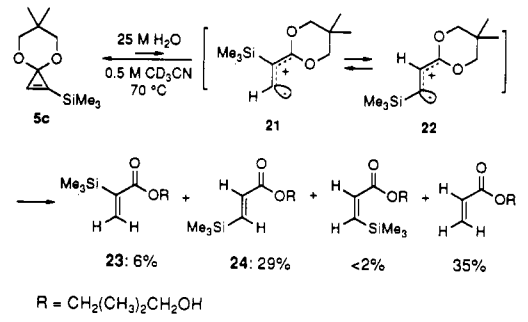
(11) For ab initio calculations, see: (a) Honjou, N.; Pacansky, J.; Yoshimine, M. *J. Am. Chem. Soc.* **1985**, *107*, 5332. (b) Yoshimine, M.; Pacansky, J.; Honjou, N. *Ibid.* **1989**, *111*, 2785. (c) Yoshimine, M.; Pacansky, J.; Honjou, N. *Ibid.* **1989**, *111*, 4198. For the stereochemistry of vinylcarbenes in photochemical conditions, see: Pincock, J. A.; Morchat, R.; Arnold, D. R. *Ibid.* **1973**, *95*, 7356.

(12) This problem may be critical especially for R = alkyl.

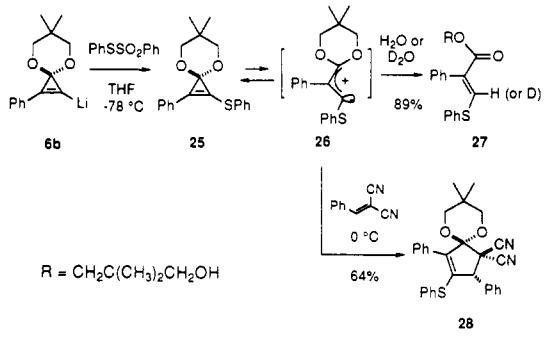
(13) See: Butler, G. B.; Herring, K. H.; Lewis, P. L.; Sharpe, V. V., III; Veazey, R. L. *J. Org. Chem.* **1977**, *42*, 679.

(14) This method was successful for the trapping of trimethylenemethane intermediates generated from methylenecyclopropanes: Nakamura, E.; Yamago, S.; Ejiri, S.; Dorigo, A. E.; Morokuma, K. *J. Am. Chem. Soc.* **1991**, *113*, 3183.

Scheme IV



Scheme V

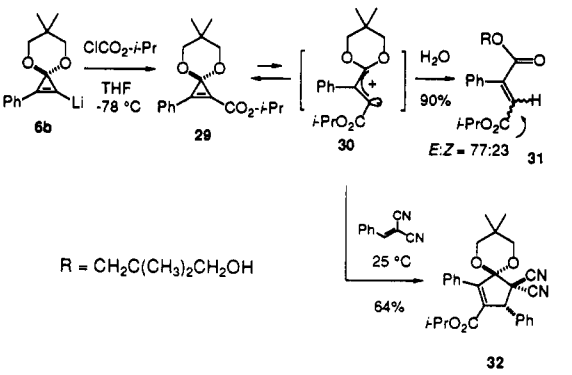


complete regioselective and *Z* stereoselective monodeuteration to give **15** exclusively.[15,16] As the D_2O concentration was reduced to 5 M and finally to 1 M, the stereospecificity eroded to 88% and to 74%, respectively. The loss of the stereospecificity is likely due to the isomerization of (*E*)-vinylcarbene **13** to **14** before trapping with water (vide infra),[17] which in turn suggests that 25 M D_2O kinetically quenches the carbene.[18]

An alkyl substituent was found to greatly retard the ring-cleavage reaction. Thus, the ethylcyclopropene **5a** barely reacted at 70 °C in aqueous CD_3CN (25 M water) and at 100 °C gave a complex mixture. On the other hand, the phenylcyclopropene **5b** was much more reactive (Scheme III). Under the kinetic quenching conditions of 25 M D_2O (vide supra), the reaction at 70 °C gave a 58:42 isomeric mixture of **19** and **20** in 83% yield. The isomer ratio was again found to change as the water concentration was reduced. Thus, the **19**/**20** ratio became 46:54 and 35:63 at 5 and 1 M concentrations of water, respectively. In no case did we detect the (*Z*)-cinnamate ester.

The hydrolysis of silylcyclopropene **5c** at 70 °C in aqueous 25 M CH_3CN was a fast reaction (Scheme IV), but was complicated by desilylation and the addition of water across the strained double bond.[19] Among the expected ring-opening products that accounted for about 35% of the product, the terminal silyl-substituted *E* isomer **24** predominated over the isomer **23**, indicating the predominant formation of **22** over **21**. The *Z* isomer of **24** could not be detected.

Scheme VI

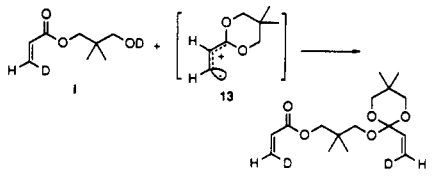


We next examined substituents of more pronounced electronic character—PhS and COO-*i*-Pr. The reaction of the lithium salt **6b** (R = Ph) with suitable electrophiles should produce the desired compounds. Thus, **6b** in THF was trapped with $PhSSO_2Ph$[20] at −78 °C and subjected to the usual aqueous workup (Scheme V). To our initial disappointment, we obtained only the unsaturated esters **27** (89% yield) instead of the desired cyclopropene **25**. When the reaction was worked up with D_2O, the β-vinyl hydrogen in **27** (86% isolated yield) was found to be completely deuterated with 100% stereospecificity as judged by ^1H and ^2H NMR spectroscopy, indicating that the β-hydrogen came from water added during workup. Evidently, the conversion of **25** to carbene **26** took place very rapidly due to the phenylthio group. The carbene was also trapped with an olefin to obtain **28** (vide infra).

Similarly, trapping of the lithium salt **6b** with ClCOO-*i*-Pr followed by workup gave the diester **31** in 66% yield, now as a 77:23 *E*/*Z* mixture (Scheme VI). The relatively stable intermediate cyclopropenecarboxylate ester **29** was isolated by nonaqueous workup (concentration and extraction with hexane; not purifiable). The ^1H NMR spectrum of the crude product (C_6D_6) was consistent with the assigned structure, exhibiting the methyne proton of the isopropoxy ester group at δ 5.15, which is a characteristic value for unsaturated esters (the isopropyl methyne of isopropyl methacrylate appears at δ 5.08 ($CDCl_3$)). The isolated crude ester **29** also afforded **31** upon the addition of water and underwent cycloaddition to an olefin (vide infra).[21]

Thermal [3 + 2] Cycloaddition. In analogy with the studies of **1**,[2] the above results demonstrate that thermolysis of cyclopropenone acetals generates substituted vinylcarbenes. Especially promising is the finding that suitably substituted cyclopropenone acetals generate carbenes below room temperature. If these carbenes undergo thermal [3 + 2] cycloaddition as in the parent system, an exceptionally mild entry to five-membered carbocycles would be available. We initiated our cycloaddition studies with stable cyclopropene **3** and the ethyl (**5a**), phenyl (**5b**), and trimethylsilyl (**5c**) derivatives.

(15) The experiment performed with a smaller amount of water was accompanied by dimer formation (~10%, see below) due to the reaction of the initial product **i** with the carbene (**13**).

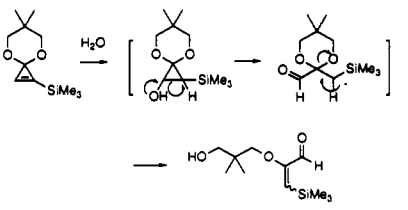


(16) The lower yield under low concentration of water is also due to a [2 + 2] cycloaddition dimer (ref 1), which formed in <26% yield.

(17) The activation energy of the hydration at 5 M concentration of water in CD_3CN was determined (at 60, 70, and 80 °C) to be 27.1 kcal/mol under the assumption that the carbene formation is rate-limiting. The effect of the two oxygen groups on the cyclopropene ring is manifested by the ca. 10 kcal/mol lowering of the activation energy as compared with that of the ring cleavage of cyclopropene and 1-methylcyclopropene (Hopf, H.; Wachholz, G.; Walsh, R. *Chem. Ber.* **1985**, *118*, 3579).

(18) Although the results are consistent with the assumed equilibration of carbene isomers (see the Discussion), solvent effects may not be totally discounted.

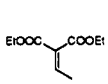
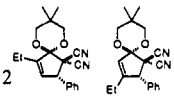
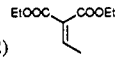
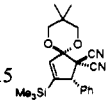
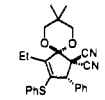
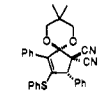
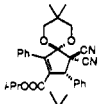
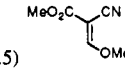
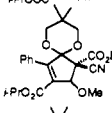
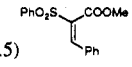
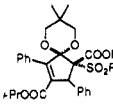
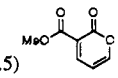
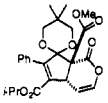
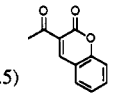
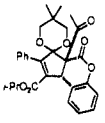
(19) We isolated an aldehyde, which was tentatively assigned as **i** by NMR spectroscopy.



(20) For the preparation of phenyl benzenethiosulfonate, see: Trost, B. M.; Massiot, G. S. *J. Am. Chem. Soc.* **1977**, *99*, 4405.

(21) Attempted trapping of the parent lithium salt of **4** gave a complex product mixture owing to the instability of the initially formed product as judged by TLC analysis. Efforts continue to optimize this reaction.

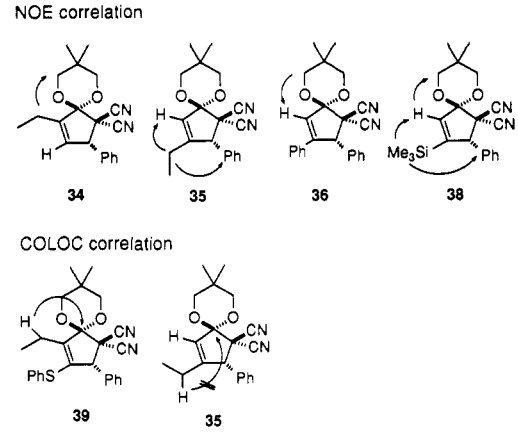
Tabel I. Thermal [3 + 2] Cycloaddition of Cyclopropenone Acetals with Electron-Deficient Olefins[a]

entry	acetal (equiv)	olefin	conditions °C, h	product	isolated yield (%)
1	**3** (2)		toluene, 80, 19	 **33**	50
	3 (1)		neat, 80, 23		62
2	**5a** (1)		toluene, 150, 12	 **34**:**35** = 71:29	82
3	**5b** (2)		benzene, 75, 15	 **36**	76
4	**5b** (2)		toluene, 80, 19	 **37**	68
5	**5c** (1)		toluene, 100, 7; 120, 15	 **38**	62
6	**44** (1.2)		THF, 15, 5	 **39**	64
7	**25** (2)		THF, 0, 5	 **28**	63
8	**29** (1)		THF, 25, 14	 **32**	64
9	**29** (1.5)		THF, 0-25, 24	 **40**	78[b]
10	**29** (1.5)		THF, 0-25, 24	 **41**	47[b]
11	**29** (1.5)		THF, 0-25, 24	 **42**	62[c]
12	**29** (1.5)		THF, 0-25, 24	 **43**	70

[a] The yields are based on pure isolated compounds except in entries 10 and 11 (^{1}H NMR with an internal standard). [b] The starting olefins and the products both consisted of a single isomer. Stereochemistry has not been assigned. [c] The product decomposed during silica gel purification.

The parent compound **3** smoothly reacted at 80 °C either with or without solvent (toluene) with diethyl ethylidenemalonate (Table I, entry 1). The ethyl compound **5a** (1 equiv) was again found to be much less reactive than **3** and was recovered at 80 °C. The reaction at 150 °C for 12 h, however, gave a 71:29 mixture of cycloadducts **34** and **35** in an 82% combined yield (entry 2), wherein the major product was due to cycloaddition of the *internally* substituted carbene **8** (R = Et). The reaction of phenylcyclopropene **5b** (1 equiv) was quite rapid at 80 °C. In contrast to the hydration results (Scheme III), however, the cycloaddition gave the adducts **36** and **37** in good yield as a single product owing exclusively to the *terminally* substituted species **18** (entries 3 and 4). A discrepancy in the regiochemistry between

Scheme VII

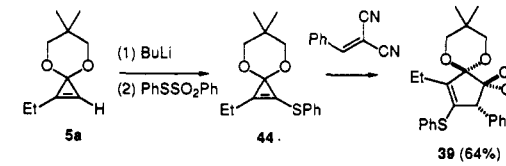


the hydration (Scheme IV) and the cycloaddition was also observed for the silyl compound **5c**. Thus, **5c** gave a single adduct **38** at 100 °C in 62% yield by the cycloaddition of *terminally* substituted carbene **22** (entry 5).

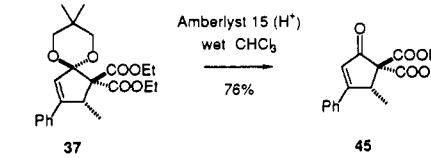
The hydration experiments (Schemes V and VI) show that the 2-phenylthio (**25**) and 2-isopropoxycarbonyl (**29**) compounds rapidly undergo highly regioselective ring opening below room temperature. This overwhelming regiochemical preference for **26** and **30** suggested that the cycloaddition would also proceed with this regioselectivity. In fact, the reaction of the isolated, crude ester **29** with a deficient amount of benzylidenemalononitrile at 20 °C in a C_6D_6 solution proceeded nearly quanitatively in about 5 h as monitored by NMR spectroscopy. In preparative experiments, **6b** was acylated and allowed to react in situ with the malononitrile (1 equiv for **6b**) in a THF solution (containing TMEDA and LiCl) to obtain **32** in a 64% yield based on **6b** (Scheme VI).

Similarly, the (phenylthio)cyclopropene **25** (prepared in situ from **6b** and $PhSS(O)_2Ph$ at −78 °C) reacted with the addition of benzylidenemalononitrile to give **28** in a 63% isolated yield at 0 °C for 5 h (Scheme V). Unlike the parent cyclopropene **1**, (phenylthio)cyclopropene **25** failed to react with a monoactivated olefin such as methacrylonitrile (which reacts with **1** in a [1 + 2] manner).[2]

The ethylcyclopropene **5a** has been similarly converted to the corresponding phenylthio derivative **44**, which also smoothly underwent cycloaddition (entry 6).



The results of the low-temperature generation and cycloaddition are summarized in entries 6–12 of Table I.[2b] The cycloadducts obtained in the present studies may serve as useful intermediates for organic synthesis. For instance, the hydrolysis of acetal **37** with wet $CHCl_3$ selectively removed the acetal moiety to give the triacyl compound in 76% isolated yield.



Structure Determination of the Cycloadducts. The regiochemistry of the cycloadducts was determined with the aid of difference NOE and ^{1}H–^{13}C COLOC (correlated spectroscopy for long-range couplings) methods.[22] Results are summarized in Scheme VII.

(22) Martin, G. E.; Zektzer, A. S. *Two-Dimensional NMR Methods for Establishing Molecular Connectivity*; VCH: New York, 1988; p 211.

Table II. Summary of the Regiochemistry of Vinylcarbene Formation and [3 + 2] Cycloaddition[a]

reactant	ethyl (**5a**)	phenyl (**5b**)	TMS (**5c**)	PhS (**25**)	COOiPr (**29**)
water (temp)	(>100 °C)[b]	58:42–33:67 (70 °C)	17:83 (70 °C)	0:100 (<25 °C)	0:100 (<25 °C)
olefin	71:29	0:100	0:100	0:100	0:100

[a] The ratios refer to the product ratios correlated to those of the internally substituted (**8**) vs the terminally substituted (**9**) vinylcarbene isomers. [b] Complex reation. See text.

The ethylcyclopropene adduct **34** showed a distinctive NOE on the acetal methylene protons upon irradiation of the methylene group of the ethyl group, while the minor adduct **35** showed NOE enhancement of the vinyl and phenyl protons upon irradiation of the methylene group of the ethyl group. Similarly, the silylcyclopropene adduct **38** showed (indicated) NOE upon irradiation of the silyl methyl group and the vinyl proton. In the phenylcyclopropene adduct **36**, the vinyl proton showed NOE enhancement upon irradiation of the acetal methylene.

The COLOC technique was used for the persubstituted cyclopentenone acetal **39**. Irradiation of a methylene proton of the ethyl group in **39** indicated weak coupling to the acetal carbon, strongly suggesting the vicinity of the proton and the carbon. Alternatively, there was no such coupling in **35**, which served as a reference alternative to the regioisomer of **39**.

Discussion

The foregoing experiments show that the [3 + 2] cycloaddition of substituted cyclopropenone acetals provides a viable synthesis of cyclopentenone derivatives. They also provide new information on the regio- and stereochemistry of vinylcarbene formation.

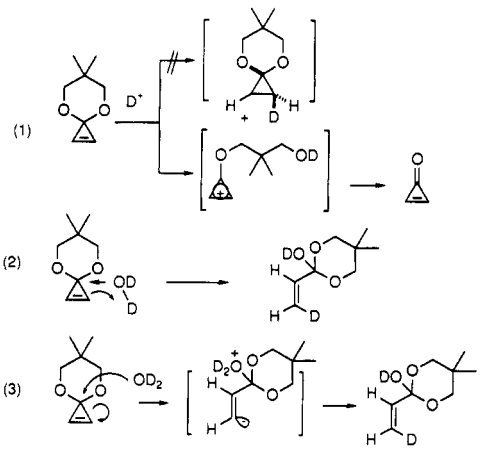
Although all experimental data fit into the vinylcarbene formation scheme as originally proposed by Boger,[2] brief comments may be necessary on alternative mechanisms of the hydrative ring cleavage of cyclopropenone acetals. Besides the vinylcarbene pathway, there are a priori three other possibilities (Scheme VIII): (1) electrophilic interaction of water with the C–C π-bond followed by ring opening of the cyclopropyl cation; (2) direct protonation of the C–C σ-bond of the cyclopropene with water; and (3) nucleophilic substitution with water at the C(3) acetal carbon. The experimental results, however, strongly argue against these possibilities.

The first pathway can be ruled out on the basis of the following discussion. First, it is known[23] that protonation of cyclopropenone acetals in a mildly acidic aqueous medium takes place at the acetal oxygen to generate stable 2π-cyclopropenium ions, which afford cyclopropenones rather than ring-opened products. We have confirmed this for a variety of substituted acetals, which invariably gave the cyclopropenones.[10] In addition, the observed regioselectivity of the hydration of **5b** and **5c** strongly argues against cyclopropyl cation formation. The second possibility is incompatible with the dependency of the stereo- and regiochemistry of the ring opening on D_2O concentration.[18] The third possibility is highly unlikely since nucleophilic attack to cyclopropenone acetal generally takes place at the strained olefinic moiety.[24] In contrast to these alternatives, the formation of free vinylcarbene intermediates offers the most consistent view of the experimental results.

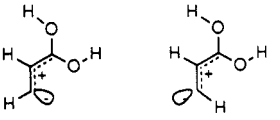
The hydration experiments provide important experimental information on the stereochemistry of the cyclopropene-to-vinylcarbene conversion. The reaction under high water concentration (Scheme II) strongly suggests that the ring-opening reaction takes place with retention of the olefin geometry since, by analogy with a vinyl anion, the sp^2 carbene terminal in **13** would be protonated with retention of the stereochemistry.

The observed concentration dependency of the stereospecificity of hydration and the stereorandom ring cleavage of cyclopropenecarboxylate **29** are intriguing. The results are qualitatively consistent with the relatively low rotational energy barrier of the

Scheme VIII



stereochemical isomerization of the singlet vinylcarbene, especially in the presence of a highly anion-stabilizing ester group at the carbene terminus.[25] The (*E*)- and (*Z*)-vinylcarbene isomers (**45** and **46**) are of nearly equal energy, as determined by ab initio calculations.[2a]



45 **46**

The regioselectivity of the hydration reaction and that of the cycloaddition are summarized in Table II. It is clear that the cyclopropenes **25** and **29**, which bear groups of strong electronic character, react via a single regioisomeric carbene, while those with less potent groups exhibit regiochemistry depending on the reactivities of the carbene acceptor (e.g., H^+ vs olefin).

The rate of the (bimolecular) cycloaddition is much slower than that of the carbene equilibration,[17] and the carbene species thus may be able to undergo equilibration with the starting cyclopropene before cycloaddition[6b] (Scheme I). Therefore, with substituents of moderate electronic characters, the regiochemistry of the cycloadditions may primarily reflect the reactivity difference between the two regioisomers **8** and **9**.

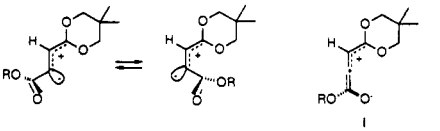
On the other hand, if only a single regioisomeric carbene is generated, then a single regioisomeric [3 + 2] cycloadduct would again result. The cycloaddition of cyclopropenes **25** and **29** may fall into this category. Another obvious consequence of such activation would be the acceleration of the overall rate of the [3 + 2] cycloaddition,[7d,26] as has been observed.

In conclusion, the thermal chemistry of substituted cyclopropenone acetals provides new information on the stereochemistry and the reactivities of singlet vinylcarbene species and has led to

(23) (a) Baucom, K. B.; Butler, G. B. *J. Org. Chem.* **1972**, *37*, 1730. (b) Breslow, R.; Oda, M. *J. Am. Chem. Soc.* **1972**, *94*, 4787.

(24) Isaka, M.; Nakamura, E. *J. Am. Chem. Soc.* **1990**, *112*, 7428. Nakamura, E.; Isaka, M.; Matsuzawa, S. *J. Am. Chem. Soc.* **1988**, *110*, 1297. Nakamura, E.; Isaka, M. *Organomet. News* **1990**, 194. See also ref 1.

(25) The stereorandomness with **29** may indicate either that the kinetic barriers to the *E* and *Z* isomers are of comparable energy, that the *E*/*Z* isomerization barrier is extremely low, or that the vinylcarbene has an allene-like structure **i** and has no relevant stereochemical issue.



i

(26) For the studies of sulfinyl and sulfone substituents on the rate of vinylcarbene formation from cyclopropenes, see: Newmann, F. M.; Lohmann, J. J. *Angew. Chem., Int. Ed. Engl.* **1977**, *16*, 323.

the development of a thermal [3 + 2] cycloaddition reaction that is useful for the synthesis of substituted cyclopentenone derivatives. Judicious choice of substituents on the cyclopropene ring effects highly regioselective preparation of cyclopentenone derivatives and also permits the cycloaddition to take place at low temperatures.

Experimental Section

General. All reactions dealing with air- or moisture-sensitive compounds were carried out in a dry reaction vessel under nitrogen. Routine chromatography was carried out as described by Still.[27] ^{1}H NMR (200, 270, and 500 MHz) and ^{13}C NMR (50, 67.5, and 125 MHz) spectra were measured for a $CDCl_3$ or CD_3CN solution of a sample on JEOL FX-200, GSX-270, and GSX-500 instruments, respectively. ^{1}H NMR spectra are reported in parts per million from internal tetramethylsilane and ^{13}C NMR spectra from $CDCl_3$ (77.0 ppm). IR spectra were recorded on a Hitachi 260-10 instrument or a JASCO IR-800; absorptions are reported in cm^{-1}. Gas chromatographic (GLC) analyses were performed on a Shimazu 8A or 14A machine equipped with glass capillary columns (0.25 mm i.d. × 25 m) coated with OV-1 or OV-17. All hydration experiments were carried out in CD_3CN at a 0.5 M concentration of the cyclopropene.

Materials. Ethereal solvents were distilled from benzophenone ketyl under nitrogen immediately before use. Acetonitrile was distilled successively from P_2O_5 and K_2CO_3 under nitrogen. Hexamethylphosphoric triamide (HMPA) was distilled from calcium hydride under nitrogen and stored over molecular sieves.

Trapping of the Vinylcarbene Generated from 3 with D_2O. In an oven-dried NMR sample tube were placed cyclopropenone acetal **3** (42.2 μL, 0.30 mmol) and D_2O (e.g., 45.2 μL, 3.0 mmol, 5 M), and the mixture was diluted with CD_3CN to make a total volume of 0.60 mL. After several freeze–thaw cycles, the tube was sealed under vacuum and heated at 80 °C for 1.5 h until the ^{1}H NMR signals due to **3** disappeared. The **15/16** ratio was determined by integration of olefinic signals (excluding those due to the homo dimer[15]), and the yield was based on the total integration of the methylene signals. Assignment of the signal was achieved by comparison with the spectrum of the corresponding protio acrylate. Experiments under various D_2O concentrations (Scheme II) were carried out in the same way. As the **15/16** mixture was inseparable, the following data were determined for the mixture.

Mixture of 15 and 16: IR (neat) 3100–3700, 2970, 2870, 1720, 1620, 1480, 1390, 1280, 1220, 1190, 1040, 850. Anal. Calcd for $C_8H_{13}O_3D$: C, 60.36; H, 8.86. Found: C, 60.45; H, 9.05.

(*Z*)-Acrylate 15: ^{1}H NMR (200 MHz, CD_3CN) δ 0.88 (s, 6 H, two CH_3), 3.28 (s, 2 H, CH_2OH), 3.93 (s, 2 H, CO_2CH_2), 5.91 (d, *J* = 10.8 Hz, 1 H, CH=CD*H*), 6.16 (dt, *J* = 2.6, 10.8 Hz, 1 H, C*H*=CDH).

(*E*)-Acrylate 16: ^{1}H NMR (200 MHz, CD_3CN) δ 0.88 (s, 6 H), 3.28 (s, 2 H), 3.93 (s, 2 H), 6.16 (dt, *J* = 2.6, 10.8 Hz, 1 H, C*H*=CDH), 6.37 (d, *J* = 18.6 Hz, 1 H, CH=CD*H*).

Protio acrylate 15 (3-hydroxy-2,2-dimethylpropyl acrylate): IR (neat) 3100–3700, 2950, 2870, 1720, 1640, 1405, 1200, 1060, 980, 810; ^{1}H NMR (200 MHz, $CDCl_3$) δ 0.99 (s, 6 H, two CH_3), 2.43–2.66 (br s, 1 H, O*H*), 3.33 (s, 2 H, CH_2OH), 4.03 (s, 2 H, CO_2CH_2), 5.87 (dd, *J* = 1.7, 10.3 Hz, 1 H, CH=C*H*H), 6.14 (dd, *J* = 10.3, 17.3 Hz, 1 H, CO_2CH=CH_2), 6.44 (dd, *J* = 1.7, 17.3 Hz, 1 H, CH=CH*H*). Anal. Calcd for $C_8H_{14}O_3$: C, 60.73; H, 8.92. Found: C, 60.45; H, 8.99.

Trapping of the Vinylcarbene Generated from 5b with H_2O. A solution of 2-phenylcyclopropenone acetal **5b** (108 mg, 0.50 mmol) and water (18.0 μL, 1.0 mmol, 1.0 M) in 0.982 mL of CH_3CN was heated at 70 °C for 6 h; the mixture was diluted with ether, and the aqueous phase was extracted with ether. The combined organic extract was washed with saturated NaCl, dried over $MgSO_4$, and concentrated to obtain a crude product. The **19/20** ratio was determined by integration of the ^{1}H NMR olefinic signals. Purification on silica gel (25% ethyl acetate/hexane) gave a mixture of **19** and **20** (60 mg, 51%). As the **19/20** mixture was inseparable, the following data were determined for the mixture. Experiments under various H_2O concentrations (Scheme III) were carried out in the same manner.

Mixture of 19 and 20: IR (neat) 3100–3700 (OH), 2950, 1720 (ester), 1640, 1210, 1180, 1060, 770, 700 (phenyl). Anal. Calcd for $C_{14}H_{18}O_3$: C, 71.77; H, 7.74. Found: C, 71.48; H, 7.64.

***exo*-Methylene 19**: ^{1}H NMR (200 MHz, $CDCl_3$) δ 0.94 (s, 6 H, two CH_3), 2.29–2.57 (br s, 1 H, O*H*), 3.32 (s, 2 H, CH_2OH), 4.09 (s, 2 H, CO_2CH_2), 5.90 (d, *J* = 2.70 Hz, 1 H, C=CH*H*), 6.39 (d, *J* = 2.7 Hz, 1 H, C=CH*H*), 7.28–7.57 (m, 5 H, phenyl CH).

(*E*)-Cinnamate 20: ^{1}H NMR (200 MHz, $CDCl_3$) δ 0.98 (s, 6 H, two CH_3), 2.29–2.57 (br s, 1 H, O*H*), 3.35 (s, 2 H, CH_2OH), 4.09 (s, 2 H, CO_2CH_2), 6.46 (d, *J* = 16.4 Hz, 1 H, C*H*=CHPh), 7.28–7.58 (m, 5 H, phenyl CH), 7.70 (d, *J* = 16.4 Hz, 1 H, CH=C*H*Ph).

D_2O Trapping of 2-Phenyl-3-(phenylthio)cyclopropenone Acetal 25. To a solution of 2-phenylcyclopropenone acetal **5b** (216 mg, 1.0 mmol) and HMPA (0.435 mL, 448 mg, 2.5 mmol) in 3.0 mL of THF was added 0.640 mL of BuLi (1.64 M in hexane, 1.05 mmol) at −78 °C, and the reaction mixture was stirred for 0.5 h. The solution was transferred into a THF solution of phenyl benzenethiosulfonate (275 mg, 1.10 mmol, 0.5 M), and the mixture was stirred for 3 h at −78 °C. To this solution was added quickly 50 mL of D_2O in THF (1:5, v/v), and the temperature was raised to room temperature. The mixture was diluted with ether and washed with a pH 7.4 phosphate buffer, and the aqueous layer was extracted with ethyl acetate twice. The combined organic extract was washed with saturated NaCl, dried over $MgSO_4$, and concentrated in vacuo to obtain a crude oily product (0.401 g). Silica gel chromatography (12 g of silica gel, 25% ethyl acetate/hexane) afforded the deuterio compound **27** (271 mg, 86% yield): IR (CCl_4) 3650, 3500, 3050, 2950, 2870, 1705, 1690, 1560, 1480, 1300, 1220, 1200, 1040, 1020, 700; ^{1}H NMR (200 MHz, $CDCl_3$) δ 0.86 (s, 6 H, two CH_3), 3.23 (br s, 2 H, CH_2OH), 4.00 (s, 2 H, CO_2CH_2), 7.34–7.44 (m, 10 H, phenyl CH). Anal. Calcd for $C_{20}H_{21}O_3SD$: C, 69.94; H, 6.16; S, 9.34. Found: C, 69.84; H, 6.12; S, 9.16.

H_2O Trapping of 2-(Isopropoxycarbonyl)-3-phenylcyclopropenone Acetal 29. To a solution of 2-phenylcyclopropenone acetal **5b** (64.9 mg, 0.30 mmol) and HMPA (0.104 mL, 0.60 mmol) in 0.60 mL of THF was added 0.183 mL of BuLi (1.64 M in hexane, 0.30 mmol), and the reaction mixture was stirred for 0.5 h at −78 °C. The solution was transferred into a solution of isopropyl chloroformate (36.4 μL, 0.30 mmol) in 0.3 mL of THF at −78 °C, and the mixture was stirred for 5 h at −78 °C. To this solution was added 0.15 mL of a pH 7.4 phosphate buffer/THF solution (1:5, v/v), and the temperature was raised to room temperature. The mixture was diluted with ether and washed with water. The aqueous layer was extracted with ethyl acetate twice. The combined organic extract was washed with saturated NaCl and dried over $MgSO_4$. Concentration in vacuo afforded a crude product (135 mg). Purification on silica gel (3 g, 25% ethyl acetate/hexane) gave 51.0 mg of **31** (64% yield). The *E*/*Z* ratio of the product was determined by ^{1}H NMR (olefinic signals). IR and ^{1}H NMR spectra were determined for the mixture.

Mixture of isomers: IR (neat) 3425, 2970, 2950, 2875, 1720, 1620, 1460, 1380, 1240, 1100, 760, 700. Anal. Calcd for $C_{18}H_{24}O_5$: C, 67.48; H, 7.55. Found: C, 66.90; H, 7.20.

***E* isomer**: ^{1}H NMR (270 MHz, $CDCl_3$) δ 0.86 (s, 6 H, two CH_3), 1.03 (d, *J* = 6.4 Hz, 6 H, two $CHCH_3$), 3.24 (s, 2 H, CH_2OH), 4.03 (s, 2 H, CO_2CH_2), 4.90 (qq, *J* = 6.4 Hz, 1 H, isopropyl CH), 7.02 (s, 1 H, olefinic CH), 7.18–7.53 (m, 5 H, phenyl CH).

***Z* isomer**: ^{1}H NMR (270 MHz, $CDCl_3$) δ 0.95 (s, 6 H, two CH_3), 1.03 (d, *J* = 6.4 Hz, 6 H, two $CHCH_3$), 3.35 (s, 2 H, CH_2OH), 4.17 (s, 2 H, CO_2CH_2), 5.09 (qq, *J* = 6.4 Hz, 1 H, isopropyl CH), 6.29 (s, 1 H, olefinic CH), 7.18–7.53 (m, 5 H, phenyl CH).

Typical Procedure for Thermal [3 + 2] Cycloaddition of Substituted Cyclopropenone Acetals with Electron-Deficient Olefins. Preparation of 5,5-Dicyano-2-ethyl-4-phenylcyclopent-2-enone 1,3-(2,2-Dimethyl)propanediyl Acetal (34) and 5,5-Dicyano-3-ethyl-4-phenylcyclopent-2-enone 1,3-(2,2-Dimethyl)propanediyl Acetal (35). 2-Ethylcyclopropenone acetal **5a** (0.53 mL, 0.50 g, 3.0 mmol) and benzylidenemalononitrile (0.46 g, 3.0 mmol) were dissolved in toluene (1.5 mL). The resulting solution was placed in a sealed tube and heated at 150 °C for 12 h. The mixture was cooled to room temperature and concentrated in vacuo. Silica gel chromatography (50 g silica gel, 5–10% ethyl acetate/hexane) afforded **34** and **35** in 58% (0.56 g) and 24% (0.23 g) yields, respectively.

34: IR (Nujol) 2950, 2910, 2850, 1460, 1370, 1130; ^{1}H NMR (200 MHz, $CDCl_3$) δ 0.91 (s, 3 H, CCH_3), 1.20 (t, *J* = 7.8 Hz, 3 H, CH_2CH_3), 1.25 (s, 3 H, CCH_3), 2.20–2.40 (m, 2 H, CH_2CH_3), 3.69 (d, *J* = 12.2 Hz, 2 H, OCH_2C), 4.10 (d, *J* = 12.2 Hz, 1 H, OCH*H*C), 4.37 (d, *J* = 12.2 Hz, 1 H, OCH*H*C), 4.55 (dd, *J* = 2.4, 4.6 Hz, 1 H, allylic CH), 5.71 (dd, *J* = 2.2, 4.6 Hz, 1 H, olefinic CH), 7.26–7.46 (m, 5 H, phenyl); ^{13}C NMR (67.5 MHz, $CDCl_3$) δ 11.48, 19.11, 22.28, 22.44, 29.66, 48.61, 57.20, 72.07, 73.07, 110.77, 112.77, 115.52, 125.97, 128.57, 128.85, 129.07, 135.55, 148.51. Anal. Calcd for $C_{20}H_{22}O_2N_2$: C, 74.50; H, 6.88; N, 8.69. Found: C, 74.43; H, 6.90; N, 8.75.

35: IR (Nujol) 2950, 2910, 2850, 1460, 1370, 1130; ^{1}H NMR (200 MHz, $CDCl_3$) δ 0.95 (s, 3 H, CCH_3), 1.07 (t, *J* = 7.9 Hz, 3 H, CH_2CH_3), 1.21 (s, 3 H, CCH_3), 1.83–2.20 (m, 2 H, CH_2CH_3), 3.66–3.86 (m, 4 H, two OCH_2C), 4.41 (br s, 1 H, allylic CH), 6.22 (dd, *J* = 2.2, 3.2 Hz, 1 H, olefinic CH), 7.19–7.43 (m, 5 H, phenyl CH); ^{13}C NMR (67.5 MHz, $CDCl_3$) δ 11.27, 21.98, 22.54, 22.79, 30.24, 51.97, 61.00, 72.78, 73.39, 108.74, 112.05, 114.42, 121.11, 128.83, 129.12, 129.49, 133.70, 151.20. Anal. Calcd for $C_{20}H_{22}O_2N_2$: C, 74.50; H, 6.88; N, 8.69. Found: C, 74.34; H, 6.94; N, 8.81.

(27) Still, W. C.; Kahn, M.; Mitra, A. *J. Org. Chem.* **1978**, *43*, 2923.

5,5-Bis(ethoxycarbonyl)-4-methylcyclopent-2-enone 1,3-(2,2-dimethyl)propanediyl acetal (33): IR ($CHCl_3$) 2950, 2850, 1720, 1480, 1260, 1140, 1090, 1060, 1040, 1020; ^1H NMR (200 MHz, $CDCl_3$) δ 0.74 (s, 3 H, CCH_3), 1.09 (d, J = 7.6 Hz, 3 H, $CHCH_3$), 1.23 (t, J = 7.6 Hz, 3 H, OCH_2CH_3), 1.25 (s, 3 H, CCH_3), 1.33 (t, J = 7.6 Hz, 3 H, OCH_2CH_3), 3.29–3.80 (m, 5 H, two OCH_2CH_3 and $CHCH_3$), 4.09–4.37 (m, 4 H, two OCH_2C), 5.88 (dd, J = 1.7, 6.4 Hz, 1 H, CCH=C*H*), 6.53 (dd, J = 2.9, 6.3 Hz, 1 H, CC*H*=CH). Anal. Calcd for $C_{17}H_{26}O_6$: C, 62.56; H, 8.03. Found: C, 62.71; H, 8.13.

5,5-Dicyano-2,4-diphenylcyclopent-2-enone 1,3-(2,2-dimethyl)propanediyl acetal (36): IR ($CHCl_3$) 2950, 2930, 2850, 2250, 1500, 1260, 1130, 700; ^1H NMR (200 MHz, $CDCl_3$) δ 0.95 (s, 3 H, CCH_3), 1.22 (s, 3 H, CCH_3), 3.81 (s, 4 H, two OCH_2C), 4.97 (d, J = 1.5 Hz, 1 H, allylic CH), 6.88 (d, J = 1.5 Hz, 1 H, olefinic CH), 7.20–7.37 (m, 5 H, phenyl). Anal. Calcd for $C_{24}H_{22}N_2O_2$: C, 77.81; H, 5.99; N, 7.56. Found: C, 78.06; H, 6.18; N, 7.40.

5,5-Bis(ethoxycarbonyl)-4-methyl-3-phenylcyclopent-2-enone 1,3-(2,2-dimethyl)propanediyl acetal (37): IR ($CHCl_3$) 2950, 2850, 1720, 1460, 1300, 1280, 1080, 1060, 700; ^1H NMR (200 MHz, $CDCl_3$) δ 0.75 (s, 3 H, CCH_3), 1.08 (d, J = 7.3 Hz, 3 H, $CHCH_3$), 1.23 (t, J = 7.1 Hz, 3 H, OCH_2CH_3), 1.29 (s, 3 H, CCH_3), 1.35 (t, J = 7.1, 3 H, OCH_2CH_3), 3.38 (dd, J = 2.4, 11.2 Hz, 1 H, OCH*H*C), 3.61 (d, J = 11.0 Hz, 1 H, OCH*H*C), 3.64 (dd, J = 2.7, 11.5 Hz, 1 H, OCH*H*C), 3.83 (d, J = 11.5 Hz, 1 H, OCH*H*C), 4.06–4.47 (m, 4 H, two OCH_2CH_3), 6.59 (d, J = 2.2 Hz, 1 H, olefinic CH), 7.29–7.38 (m, 5 H, phenyl CH). Anal. Calcd for $C_{22}H_{30}O_6$: C, 68.63; H, 7.51. Found: C, 68.88; H, 7.75.

5,5-Dicyano-4-phenyl-3-(trimethylsilyl)cyclopent-2-enone 1,3-(2,2-dimethyl)propanediyl acetal (38): IR (Nujol) 2950, 2900, 2850, 1460, 1370, 1140, 1120; ^1H NMR (200 MHz, $CDCl_3$) δ −0.05 (s, 9 H, $Si(CH_3)_3$), 0.99 (s, 3 H, CCH_3), 1.15 (s, 3 H, CCH_3), 3.67–3.91 (m, 4 H, two OCH_2C), 4.57 (d, J = 1.8 Hz, 1 H, allylic CH), 6.51 (d, J = 1.8 Hz, 1 H, olefinic CH), 7.19–7.43 (m, 5 H, phenyl CH); ^{13}C NMR (67.5 MHz, $CDCl_3$) δ −1.65, 22.08, 22.53, 30.32, 51.36, 63.51, 72.75, 73.64, 111.11, 112.31, 114.74, 128.66, 129.17, 129.65, 134.96, 135.63, 151.09. Anal. Calcd for $C_{21}H_{26}O_2N_2Si$: C, 68.81; H, 7.15; N, 7.64. Found: C, 69.04; H, 7.33; N, 7.39.

Cycloaddition of 2-(Isopropoxycarbonyl)cyclopropenone Acetal. Preparation of 5,5-Dicyano-2,4-diphenyl-3-(isopropoxycarbonyl)cyclopent-2-enone 1,3-(2,2-Dimethyl)propanediyl Acetal (32). To a solution of 2-phenylcyclopropenone acetal **5b** (64.9 mg, 0.30 mmol) and HMPA (0.104 mL, 0.60 mmol) in 0.60 mL of THF was added 0.187 mL of BuLi (1.65 M in hexane, 0.31 mmol), and the reaction mixture was stirred for 0.5 h at −78 °C. The solution was transferred into a solution of isopropyl chloroformate (0.0683 mL, 0.60 mmol) in 0.6 mL of THF at −78 °C, and the mixture was stirred for 4 h. To this solution was added benzylidenemalononitrile (46.3 mg, 0.30 mmol), and the temperature was raised to room temperature. After stirring for 14 h, the mixture was diluted with ether and poured into saturated $NaHCO_3$. The organic layer was separated, washed with water, and then with saturated NaCl, and dried over Na_2SO_4. Concentration in vacuo afforded a crude oil (144 mg). Purification on silica gel (4.5 g, 25% ethyl acetate/hexane) gave 87.2 mg (64% yield) of **32**: IR (Nujol) 2950, 2850, 1700, 1250, 1200, 1100, 1060, 700; ^1H NMR (200 MHz, $CDCl_3$) δ 0.65 (d, J = 8.20 Hz, 3 H, $CHCH_3$), 0.68 (s, 3 H, CCH_3), 0.90 (s, 3 H, CCH_3), 0.96 (d, J = 8.20 Hz, 3 H, $CHCH_3$), 3.57 (ddd, J = 2.48, 4.95, 15.2 Hz, 2 H, OCH_2C), 4.07 (dd, J = 3.8, 15.2 Hz, 2 H, OCH_2C), 4.75 (qq, J = 8.4 Hz, 1 H, olefinic CH), 4.93 (s, 1 H, allylic CH), 7.38 (br s, 10 H, phenyl CH); ^{13}C NMR (50 MHz, $CDCl_3$) δ 20.82, 21.43, 22.31, 22.74, 30.21, 48.85, 57.69, 68.89, 72.68, 73.00, 110.25, 112.44, 114.54, 127.61, 128.72, 128.89, 129.21, 131.81, 133.65, 134.49, 149.14, 162.56. Anal. Calcd for $C_{28}H_{28}O_4N_2$: C, 73.66; H, 6.18; N, 6.14. Found: C, 73.89; H, 6.45; N, 6.00.

5-Cyano-3-(isopropoxycarbonyl)-4-methoxy-5-(methoxycarbonyl)-2-phenylcyclopent-2-enone 1,3-(2,2-dimethyl)propanediyl acetal (40): IR (neat) 2950, 2250 (CN), 1740, 1720, 1600, 1460, 1380, 1250, 1100, 1080, 850, 700 (phenyl); ^1H NMR (270 MHz, $CDCl_3$) δ 0.60 (s, 3 H, CCH_3), 0.84 (s, 3 H, CCH_3), 0.92 (d, J = 6.4 Hz, 3 H, $CHCH_3$), 1.04 (d, J = 6.0 Hz, 3 H, $CHCH_3$), 3.32 (dd, J = 2.0, 11.0 Hz, 1 H, OCH*H*C), 3.68 (s, 3 H, $COCH_3$), 3.76 (d, J = 11.6 Hz, 1 H, OCH*H*C), 3.90 (s, 3 H, CO_2CH_3), 4.29 (d, J = 11.6 Hz, 1 H, OCH*H*C), 4.90 (qq, J = 6.0 Hz, 1 H, isopropyl CH), 4.98 (s, 1 H, allylic CH), 7.22–7.72 (m, 5 H, phenyl CH); ^{13}C NMR (67.5 MHz, $CDCl_3$) δ 21.1, 21.5, 22.2, 22.9, 30.0, 53.6, 60.3, 60.6, 68.5, 72.4, 72.6, 85.0, 110.1, 115.2, 127.4, 128.2, 128.9, 132.4, 133.5, 151.3, 162.8, 165.6. Anal. Calcd for $C_{24}H_{29}O_7N$: C, 66.49; H, 6.74; N, 3.25. Found: C, 66.19; H, 6.94; N, 2.95. The starting olefin[28] and the product (**40**) both consisted of a single isomer.

2,4-Diphenyl-3-(isopropoxycarbonyl)-5-(methoxycarbonyl)-5-(phenylsulfonyl)cyclopent-2-enone 1,3-(2,2-dimethyl)propanediyl acetal (41): IR (CCl_4) 2950, 1750, 1730, 1340, 1240, 1180, 700, 570; ^1H NMR ($CDCl_3$, 270 MHz) δ 0.46 (s, 3 H, CCH_3), 0.74 (d, J = 6.4 Hz, 3 H, $CHCH_3$), 0.81 (s, 3 H, CCH_3), 0.94 (d, J = 6.4 Hz, $CHCH_3$), 3.32 (d, J = 10.8 Hz, 1 H, OCH*H*C), 3.36 (s, 3 H, CO_2CH_3), 3.41 (d, J = 10.8 Hz, 1 H, OCH*H*C), 3.81 (d, J = 10.8 Hz, 1 H, OCH*H*C), 4.12 (d, J = 10.8 Hz, 1 H, OCH*H*C), 4.69 (qq, J = 6.0 Hz, 1 H, isopropyl CH), 7.15–7.40 (m, 10 H, phenyl CH), 7.50–7.70 (m, 3 H, $SO_2C_6H_5$), 8.02 (m, 2 H, $SO_2C_6H_5$). Anal. Calcd for $C_{34}H_{36}O_8S$: C, 67.53; H, 6.00; S, 5.30. Found: C, 67.23; H, 5.72; S, 5.20. The starting olefin[29] and the product both consisted of a single isomer.

Cycloadduct with Methyl 2-Oxo-2*H*-pyran-3-carboxylate (42). This compound decomposed on silica gel purification, and the yield was determined by ^1H NMR analysis using an internal standard: ^1H NMR (200 MHz, $CDCl_3$) δ 0.43 (s, 3 H, CCH_3), 0.89 (s, 3 H, CCH_3), 0.98 (d, J = 6.0 Hz, 3 H, $CHCH_3$), 1.31 (d, J = 6.0 Hz, $CHCH_3$), 3.39–3.54 (m, 4 H, two acetal methylenes), 4.04 (dd, J = 2.6 Hz, 1 H, bis-allylic CH), 4.86 (qq, J = 6.0 Hz, 1 H, isopropyl CH), 5.48 (dd, J = 2.6, 6.4 Hz, 1 H, OCH=C*H*), 6.45 (dd, J = 2.6, 6.4 Hz, 1 H, OC*H*=CH), 7.09–7.57 (m, 5 H, phenyl CH).

Cycloadduct with 2-acetylcoumarin (43): IR (CCl_4) 2950, 2880, 1760 (lactone), 1720 (ester), 1460, 1380, 1240, 1200, 1160, 1100, 700 (phenyl); ^1H NMR ($CDCl_3$, 270 MHz) δ 0.38 (s, 3 H, CCH_3), 0.86 (d, J = 6.0 Hz, 3 H, $CHCH_3$), 1.01 (s, 3 H, CCH_3), 1.05 (d, J = 6.0 Hz, $CHCH_3$), 2.60 (s, 3 H, O=CCH_3), 3.16 (d, J = 11.6 Hz, 1 H, OCH*H*C), 3.30 (dd, J = 1.8, 10.0 Hz, OCH*H*C), 3.46 (d, J = 11.6 Hz, 1 H, OCH*H*C), 3.56 (dd, J = 1.8, 10.0 Hz, 1 H, OCH*H*C), 4.80 (s, 1 H, allylic CH), 4.92 (qq, J = 6.2 Hz, 1 H, isopropyl CH), 7.02–7.16 (m, 4 H, aromatic CH), 7.22–7.40 (m, 5 H, phenyl CH). Anal. Calcd for $C_{28}H_{30}O_7$: C, 71.00; H, 6.16. Found: C, 71.00; H, 5.90.

Typical Procedure for the Cycloaddition of 2-(Phenylthio)cyclopropenone Acetal. Preparation of 5,5-Dicyano-2,4-diphenyl-3-(phenylthio)cyclopent-2-enone 1,3-(2,2-Dimethyl)propanediyl Acetal (28). To a solution of 2-phenylcyclopropenone acetal **5b** (128 mg, 0.60 mmol) and HMPA (0.260 mL, 269 mg, 1.50 mmol) in 1.5 mL of THF was added 0.364 mL of BuLi (1.65 M in hexane, 0.60 mmol) at −78 °C, and the reaction mixture was stirred for 20 min at this temperature. The solution was transferred into a THF solution of phenyl benzenethiosulfonate (226 mg, 0.90 mmol, 1 M) via a cannula, and the mixture was stirred for 2 h at −78 °C. To this solution was added benzylidenemalononitrile (46.3 mg, 0.30 mmol), and the temperature was raised to 0 °C. After stirring for 5 h at 0 °C, the reaction was terminated by the addition of a pH 7.4 phosphate buffer in THF (0.15 mL, 1:5). The mixture was washed with the phosphate buffer, and the aqueous layer was extracted with ethyl acetate. The combined organic extract was washed with saturated NaCl, dried over Na_2SO_4, and concentrated in vacuo to afford a crude oily product (0.413 g). Silica gel chromatography (120 g silica gel, 25% ethyl acetate/hexane) afforded **28** (90.5 mg, 64% yield): IR (neat) 3050, 3030, 2950, 2860, 2250, 1570, 1500, 1480, 1440, 1300, 1200, 1180, 1160, 920, 740, 700; ^1H NMR (200 MHz, $CDCl_3$) δ 0.77 (s, 3 H, CCH_3), 0.80 (s, 3 H, CCH_3), 3.48 (dd, J = 2.0, 12.0 Hz, 1 H, OCH*H*C), 3.71 (dd, J = 2.0, 12.0 Hz, 1 H, OCH*H*C), 3.98 (d, J = 12.4 Hz, 1 H, OCH*H*C), 4.07 (d, J = 12.0 Hz, 1 H, OCH*H*C), 4.27 (s, 1 H, olefinic CH), 7.03–7.60 (m, 15 H, aromatic CH). Anal. Calcd for $C_{30}H_{26}O_2N_2S$: C, 75.28; H, 5.48; N, 5.85; S, 6.70. Found: C, 75.00; H, 5.48; N, 6.00; S, 6.42.

Preparation of 5,5-Dicyano-2-ethyl-4-phenyl-3-(phenylthio)cyclopent-2-enone 1,3-(2,2-dimethyl)propanediyl acetal (39): IR (Nujol) 2250, 1640, 1300, 1240, 1150, 1110, 890, 750; ^1H NMR (200 MHz, $CDCl_3$) δ 0.87 (s, 3 H, CCH_3), 1.27 (t, J = 8.0 Hz, 3 H, CH_2CH_3), 1.29 (s, 3 H, CCH_3), 2.52 (q, J = 8.0 Hz, 2 H, CH_2CH_3), 3.32 (dd, J = 2.6, 12.2 Hz, 1 H, OCH*H*C), 3.79 (dd, J = 2.6, 12.2 Hz, 1 H, OCH*H*C), 4.07 (d, J = 12.4 Hz, 1 H, OCH*H*C), 4.17 (s, 1 H, allylic, CH), 4.26 (d, J = 12.0 Hz, 1 H, OCH*H*C), 6.95–7.37 (m, 10 H, aromatic CH); ^{13}C NMR (67.5 MHz, $CDCl_3$) δ 13.83, 19.53, 22.28, 22.51, 29.53, 46.47, 60.22, 72.57, 72.71, 110.85, 113.38, 114.89, 128.34, 128.42, 128.97, 129.09, 129.50, 129.70, 132.96, 134.09, 135.37, 144.42. Anal. Calcd for $C_{26}H_{26}O_2N_2S$: C, 72.53; H, 6.09; N, 6.51; S, 7.45. Found: C, 72.75; H, 6.39; N, 6.43; S, 7.20.

Hydrolysis of the Acetal. Preparation of 5,5-Bis(ethoxycarbonyl)-4-methyl-3-phenyl-2-cyclopenten-1-one (45). To a solution of 5,5-bis(ethoxycarbonyl)-4-methyl-3-phenyl-2-cyclopentenone acetal (33.0 mg, 0.10 mmol) and water (9.4 μL, 0.50 mmol) in 0.5 mL of $CHCl_3$ was added Amberlyst 15 (ca. 10 mg), and the suspension was stirred at room temperature for 3 h. Amberlyst 15 was removed by filtration, and the filtrate was concentrated to obtain a viscous oily product. Purification on silica

(28) For the preparation, see ref 2c.

(29) For the preparation, see: Happer, D. A. R.; Steenson, B. E. *Synthesis* **1980**, 806.

gel (1 g, 25% ethyl acetate/hexane) afforded **45** (23.1 mg, 73%): IR (neat) 2975, 2925, 1720, 1700, 1600, 1460, 1440, 250, 1180, 1040, 760, 690; ^{1}H NMR (270 MHz, $CDCl_3$) δ 0.92 (s, 3 H, $CC\underline{H}_3$), 1.21 (d, J = 7.3 Hz, 3 H, $CHC\underline{H}_3$), 1.31 (t, J = 7.1 Hz, 6 H, two $OCH_2C\underline{H}_3$), 4.13-4.50 (m, 5 H, two $OC\underline{H}_2CH_3$, $C\underline{H}CH_3$), 6.35 (s, 1 H, olefinic CH), 7.43-7.53 (m, 3 H, phenyl CH), 7.56-7.67 (m, 2 H, phenyl CH). Anal. Calcd for $C_{18}H_{20}O_5$: C, 68.34; H, 6.37. Found: C, 68.54; H, 6.60.

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Electronic Stabilization of Nucleophilic Carbenes[1]

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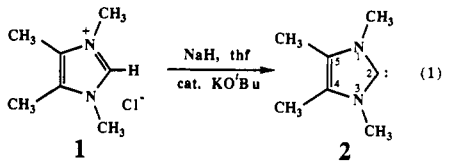
Abstract: Four new stable nucleophilic carbenes have been synthesized and structurally characterized. The remarkable ability of the imidazole nucleus to stabilize a carbene center at the C-2 position is demonstrated by the isolation of 1,3,4,5-tetramethylimidazol-2-ylidene. The isolation of three imidazol-2-ylidenes that bear aryl substituents is counter to speculations based on previous reports.

Introduction

Carbenes[2] are two-coordinate carbon compounds that have two nonbonding electrons and no *formal charge*[3] on the carbon. These types of two-coordinate carbon compounds essentially represent carbon in an oxidation state of II. Oxidation state II is well represented in carbon chemistry by stable monocoordinated carbon centers such as those in carbon monoxide (C=O) and isonitriles (R-N=C). In biochemistry, structures such as thiamine-derived intermediates can be formulated as either zwitterions (ylides) or carbenes.[4] However, in the absence of isolable model compounds, the best characterization for these important intermediates remains a matter for speculation. Stable compounds in the carbene category have been made only recently, and definite structural and electronic information is now available.[5-7] Apparently, the stability of these carbenes is derived from a combination of steric and electronic factors. These factors achieve the stability necessary for isolation. We now describe the syntheses and structures of four new stable carbenes. Structural features of these new carbenes suggest that steric factors are unimportant in contributing to the stability of the imidazol-2-ylidenes.

Results and Discussion

Most remarkably, carbene **2** (1,3,4,5-tetramethylimidazol-2-ylidene) is obtained in 89% yield when 1,3,4,5-tetramethylimidazolium chloride (**1**) is treated with 1 equiv of sodium hydride and 5 mol % potassium *tert*-butoxide in tetrahydrofuran (thf) (eq 1). Carbene **2** is a colorless crystalline solid melting at 109-110 °C. A previously melted sample of **2** showed no depression of the melting point upon remelting. Samples of **2** could be purified by recrystallization from toluene or vacuum sublimation. The ^{1}H NMR spectrum (thf-d_8) shows only two resonances of equal area at 2.01 and 3.48 for the methyls on carbon and nitrogen. The ^{13}C NMR spectrum has a resonance at δ 213.7 similar to the value of 211.4 found for the carbene center of **3** (Table I).



1 **2** (1)

Cooling a toluene solution of **2** gave crystals suitable for X-ray diffraction studies. The resulting structure for **2** is shown in Figure 1. Selected bond lengths and angles are given in Table II. The molecule sits on a crystallographic 2-fold axis. The five ring atoms are planar by symmetry, and the methyl carbons at nitrogen and carbon deviate by 0.023 and 0.049 Å, respectively, from the molecular plane.

The KANVAS[8] drawing in Figure 1 illustrates the unencumbered geometry of the carbene center in **2**. The lack of significant steric hindrance in **2** starkly contrasts the previously synthesized stable carbene, 1,3-di(1-adamantyl)imidazol-2-ylidene (**3**).[5] The structures of **2** and **3** are quite similar, but there are some slight differences that are noteworthy. The valence angle at the carbene center in **2** is 0.7° smaller than the same angle in **3**. The ring internal angle at nitrogen is 1.3° larger for **2** compared to **3**. The $N_{1(3)}$-C_2 bond distance is 0.7 pm shorter in **2** than in **3**. The $N_{1(3)}$-$C_{5(4)}$ bond distance is 1.2 pm longer and the ring C=C distance is 1.4 pm longer in **2** than in **3**. These differences bring the experimental structure of **2** very close to the calculated structure for the unsubstituted imidazol-2-ylidene.[9] This result supports our earlier assumption[9] that small differences in the calculated structure for the unsubstituted imidazol-2-ylidene and the experimental structure of **3** are the result of steric influences of the 1-adamantyl substituent on the imidazole ring. Very similar trends can be seen among the structures observed for the 1,3-di(1-adamantyl)imidazolium and 1,3-dimethylimidazolium ions and the structure calculated for the unsubstituted imidazolium ion.

We also have observed another sterically unencumbered carbene, 1,3-dimethylimidazol-2-ylidene (**4**), in solution. Although

(1) Dedicated to Dr. H. E. Simmons, Jr. on the occasion of his retirement.
(2) The term "carbene" was first used in connection with this type of structure in a Chicago taxi; see: Doering, W. v E.; Knox, L. H. *J. Am. Chem. Soc.* **1956**, *78*, 4947 footnote 9.
(3) The *formal charge* at an atom is determined by its valence bond representation. The significance of *formal charges* has been discussed elsewhere: Pauling, L. *The Nature of the Chemical Bond*, 3rd ed.; Cornell University Press: Ithaca, NY, 1960; pp 8 and 9 and references therein.
(4) For a recent paper on the generation of thiamine-related intermediates, see: Bordwell, F. G.; Satish, A. V. *J. Am. Chem. Soc.* **1991**, *113*, 985. For a more comprehensive review, see: Kluger, R. *Chem. Rev.* **1987**, *87*, 863.
(5) Arduengo, A. J., III; Harlow, R. L.; Kline, M. *J. Am. Chem. Soc.* **1991**, *113*, 361.
(6) Bertrand et al. have reported a stable compound than can be characterized either as a λ^3-phosphinocarbene or as λ^5-phosphaacetylene structures; see: Igau, A.; Grutzmacher, H.; Baceiredo, A.; Bertrand, G. *J. Am. Chem. Soc.* **1988**, *110*, 6463 and Igau, A.; Baceiredo, A.; Trinquier, G.; Bertrand, G. *Angew. Chem., Int. Ed. Engl.* **1989**, *28*, 621. Recent theoretical models suggest that the best description is as a λ^5-phosphaacetylene; see: Dixon, D. A.; Dobbs, K. D.; Arduengo, A. J., III; Bertrand, G. *J. Am. Chem. Soc.* **1991**, *113*, 8782.
(7) Regitz, M. *Angew. Chem., Int. Ed. Engl.* **1991**, *30*, 674.
(8) These drawings were made with the KANVAS computer graphics program. This program is based on the program SCHAKAL of E. Keller (Kristallographisches Institute der Universitat Freiburg, Germany), which was modified by A. J. Arduengo, III (Du Pont Central Research, Wilmington, DE) to produce the back and shadowed planes. The planes bear a 50-pm grid and the lighting source is at infinity so that shadow size is meaningful.
(9) Dixon, D. A.; Arduengo, A. J., III *J. Phys. Chem.* **1991**, *95*, 4180.

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