we suggest that the low yield of ozonide is due to the fact that the anti carbonyl oxide cannot cyclize intramolecularly, and so intermolecular reaction (oligomerization) competes successfully.

To test this, we designed the deuterium-labeled substrates **1d** and **2d** (Scheme II). Ozonation of each of these proceeds to a quasi-symmetrical intermediate, in which the geometry of the carbonyl oxide is differentiated only by the isotope label on the tethered aldehydes. Since the kinetic secondary isotope effect for cyclization of the carbonyl oxide with unlabeled vs labeled aldehyde is quite small,[7] any selectivity in this process, as measured by the ratio of isotopomeric ozonides, must be attributed to the carbonyl oxide geometry.

The requisite aldehydes were prepared by reduction of the corresponding esters,[8,9] a route which can be modified to produce either the labeled or unlabeled systems. Ozonolysis of **1** (pentane, −78 °C) provided a 50% yield of the ozonide **5**, after chromatography. This product was characterized by signals in the ^{1}H NMR at 9.77 ppm (t, $J = 1.4$ Hz) and 5.76 (br s) for the aldehyde and ozonide bridgehead protons, respectively. Repetition of the experiment, using labeled aldehyde **1d**, provided a comparable yield of a mixture of ozonide isotopomers **5d** and **6d**, in a ratio of 8:1, respectively, as determined by NMR integration. This regioselectivity for the cyclization indicates clearly that there is a strong preference for cyclization of the carbonyl oxide with the newly formed aldehyde, in accord with the prediction that **1d** will lead preferentially to carbonyl oxide (*E*)-**3**.

Ozonolysis of cyclohexene **2** under the same conditions provided a 67% yield of the monomeric ozonide **7**. The structure of **7** was confirmed by spectroscopic analysis, including the characteristic ^{1}H NMR signals at 9.77 (br s) and 5.62 ppm. This remarkably high yield of ozonide stands in contrast to the results obtained with other cyclohexenes and suggests that formation of cyclohexene ozonide is not limited by entropic factors. Finally, when the labeled substrate **2d** was treated with ozone, the monomeric ozonide was found to consist of the isotopomers **7d** and **8d** in a ratio of 1:23. The very high selectivity for cyclization of the carbonyl oxide to the deuterated aldehyde is convincing evidence that the carbonyl oxide has the geometry represented in (*Z*)-**4**, in accord with predictions based on the conformation of the primary ozonide.

These experiments provide the first straightforward assessment of the stereochemistry of carbonyl oxide intermediates. Clearly, the highly regioselective reaction from each of the cycloalkene precursors demonstrates that the carbonyl oxide is formed with good stereoselectivity and that the stereochemical integrity of this intermediate is maintained.[10] Likewise, the relationship of cyclization pathway to carbonyl oxide geometry is that expected for a concerted cycloaddition pathway. Most importantly, these results establish the viability of intramolecular trapping for assignment of carbonyl oxide geometry. Further applications of this method are in progress and will be reported in due course.

Acknowledgment. We thank the National Science Foundation (CHE 9108712) for support of this project, as well as for the support of the NMR facilities (CHE 89-08304) used in this work.

Supplementary Material Available: ^{1}H NMR spectra for **1**, **1d**, **2**, **2d**, and their ozonolysis products (8 pages). Ordering information is given on any current masthead page.

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(9) The aldehydes were invariably contaminated with the isomeric, exocyclic alkenes. These gave different products on ozonolysis and did not interfere with the isotopomer assay.

(10) (a) Cremer, D. *J. Am. Chem. Soc.* **1979**, *101*, 7199–7205. (b) Keul, H.; Kuczkowski, R. L. *J. Org. Chem.* **1985**, *50*, 3371–3376. (c) Wojciechowski, B. J.; Pearson, W. H.; Kuczkowski, R. L. *J. Org. Chem.* **1989**, *54*, 115–121.

The Temporary Silicon Connection in the Control of the Regiochemistry of 4 + 2 Cycloadditions

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The "temporary silicon connection" achieves the regiospecific, and often stereoselective, formation of carbon–carbon bonds by temporarily bringing together two reaction partners by means of an eventually removable silicon atom. During the last few years we have investigated the usefulness of that concept in a variety of ionic, radical, photochemical, and cycloaddition processes.[1] This communication is concerned with 4 + 2 cycloadditions.

Scheme I illustrates the process in a simple case. In this prototypical case, the overall reaction **1** → **4**[4] is equivalent to the addition of ethylene, acting as a dienophile, to diene **1**. No question of regiochemistry arises in this case when the silicon is simply removed from the adduct, but even in this simple case, the regiochemistry implicit in the process is brought forth when the silicon atom is replaced by a hydroxyl, as in **1** → **5**. The regiocontrol which results when substituted ethylenes are used in the temporary silicon connection process is illustrated by the transformation of **6**[5] to **7**[7,9] (Scheme II).

Scheme III illustrates some of the numerous cyclizations involving vinylsilanes which we have investigated. The formation of **15**[10] is notable in that it involves addition to a 1,1-disubstituted diene, a type of substitution which would not be expected to be productive in a bimolecular mode.

The effective use of silicon-tethered simple alkenes as dienophiles augured well for the use of more typical dienophiles such as acrylic esters as partners in the silicon-tethered Diels–Alder

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(1) Inter alia, see: (a) Keitz, P. Ph.D. Thesis, Columbia University, **1988**. (b) Lambert, P. Ph.D. Thesis, Columbia University, **1991**. (c) Stork, G. *Abstracts of 32nd National Organic Chemistry Symposium*; Organic Chemistry Division, ACS, 1991; p 115. (d) Stork, G.; Suh, H. S.; Kim, G. *J. Am. Chem. Soc.* **1991**, *113*, 7054. (e) Stork, G.; Kim, G. *J. Am. Chem. Soc.* **1992**, *114*, 1087. For internal 4 + 2 additions in which the silicon connection involves oxygen atoms, see: Craig, D.; Reader, J. C. *Tetrahedron Lett.* **1992**, *33*, 4073 and references therein.

(2) All 4 + 2 cycloaddition reactions were carried out in benzene solutions in sealed tubes. They can also be performed in solvents (chlorobenzene, anisole, ...) of suitable boiling points.

(3) Use of vinyl*diphenyl*chlorosilane instead of the dimethyl analog gave very similar results.

(4) The structures of the various cycloadducts were established by ^{1}H NMR and NOE measurements.

(5) Most of the silylated derivatives of sorbyl alcohol were made by reaction of the required alkenyl Grignard or lithium derivative with (*N*,*N*-dimethylamino)dimethylchlorosilane, followed by reaction of the resulting (*N*,*N*-dimethylamino)alkenylsilane with **1**.[6]

(6) Stork, G.; Keitz, P. *Tetrahedron Lett.* **1989**, *30*, 6981.

(7) Replacement of the carbon–silicon bond by a carbon–hydrogen bond (hydrodesilylation) has been shown[8] to require the presence in the substrate of a hydroxyl substituent capable of forming a ring (no larger than five-membered) with the silicon atom (cf. **3** → **4**), a condition which is a corollary of the presence of an allylic hydroxyl in the original diene (e.g., **1** in this work). The fluoride-induced hydrodesilylations referred to in this communication presumably involve carbanion or radical intermediates, and there is, therefore, no correspondence between the stereochemistry of the intermediate siloxane adducts and that of their desilylation products. In contrast, the transformation of the carbon–silicon into a carbon–oxygen bond by reaction with various peroxides takes place with retention of configuration (essentially a Baeyer–Villiger reaction).[9] Thus, in addition to leading to regiospecific formation of hydroxycyclohexenes, replacement of the silicon by a hydroxyl gives ratios of epimeric alcohols which correspond to the stereochemistry of their silane precursors, presumably reflecting the partition between endo and exo transition states in the 4 + 2 cycloadditions.

(8) Hudrlik, P. F.; Hudrlik, A.; Kulkarni, K. A. *J. Am. Chem. Soc.* **1982**, *104*, 6809.

(9) (a) Tamao, K.; Akita, H.; Iwahara, T.; Kanatani, R.; Yoshida, J.; Kumada, M. *Tetrahedron* **1983**, *39*, 983. (b) Fleming, I.; Henning, R.; Plant, H. *J. Chem. Soc., Chem. Commun.* **1984**, 29.

(10) The structure was established by conversion to the corresponding 1,2,4-trimethylcyclohexanes (Pd–H_2; TsCl–pyridine; LAH) and comparison with authentic, stereodefined samples (from Wiley Organics, Coshocton, OH).

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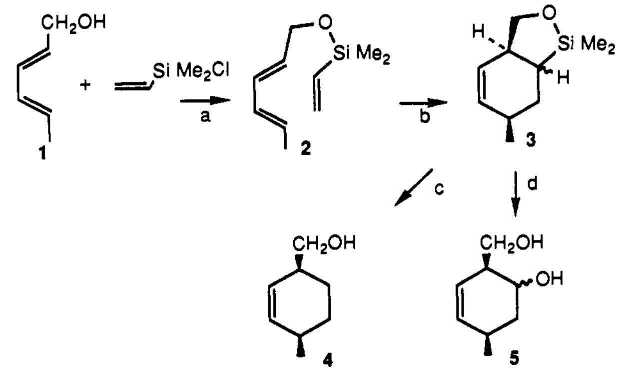
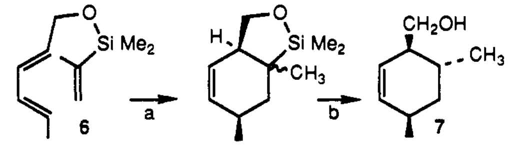
Scheme I[a]



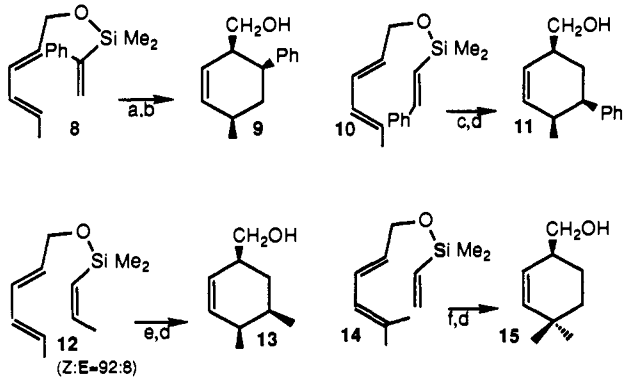
[a] Conditions: (a) Et_3N-THF; (b) 160 °C,[2] 3.5 h; 70%; (c) 4 equiv of TBAF-DMF, 75 °C, 4 h; 75%; (d) 1 equiv of TBAF-DMF, 10 equiv of 30% H_2O_2, 55 °C, 2 h; 85% (cis-1,2:trans-1,2 = 70:30).

Scheme II[a]



[a] Conditions: (a) 160 °C, 5 h; 80%, 2 isomers (60:40); (b) as in 3 → 4; 65% (1 isomer; see footnote 7).

Scheme III[a]

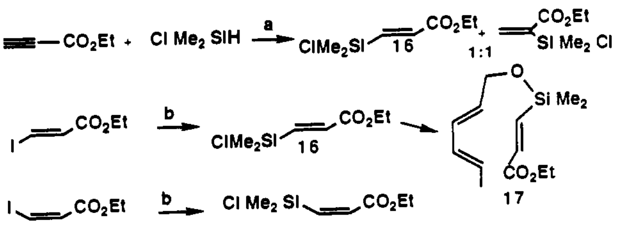


[a] Conditions: (a) 160 °C, 4 h; 75%; (b) TBAF-DMF; 85%; (c) 180 °C, 10 h; 80%; (d) TBAF-DMF, 85% (cis-4,5:trans-4,5 = 85:15); (e) 200 °C, 10 h; 45% (cis-4,5:trans-4,5 = 81:19); (f) 200 °C, 30 h; 50–60%.

context. This proved very successful. We were able to prepare the (*E*)-(chlorosilyl)acrylate **16** in two different ways, as shown in Scheme IV: as a component of a 1:1 mixture of regioisomers[11] or, regiospecifically, from (*E*)-ethyl 3-iodoacrylate.[12,13] Addition of **16** to **1** then gave the silicon-tethered acrylate **17** (50% from the iodoacrylate).

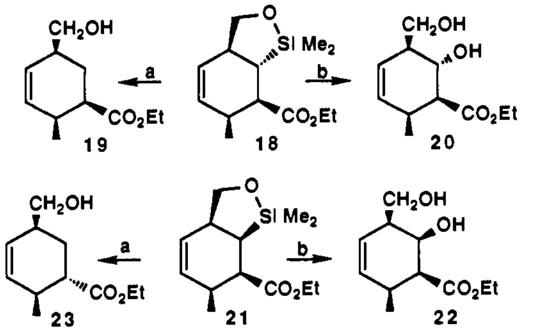
Cyclization of **17** readily (4–6 h, 80 °C) gave **18** (see Scheme V), the product of endo addition, in 90% yield. A similar sequence starting with (*Z*)-ethyl 3-iodoacrylate[12] gave the corresponding product of endo addition, as judged by its conversion to **22**. In this particular case, however, the initial, unstable, all-cis adduct **21** was epimerized by fluoride ion in the course of the desilylation process, with the formation of **23**.

Scheme IV[a]



[a] Conditions: −100 °C; then 1 equiv of acetyl chloride.

Scheme V[a]



[a] Conditions: (a) 2 equiv of TBAF; DMF, 60 °C, 4 h; 75%; (b) as in 3 → 5; 80%.

The important feature of *controlled regiochemistry* which the temporary silicon connection can afford in the context of 4 + 2 cycloadditions is particularly well illustrated by the syntheses of **20** and **22**, in which, in addition, four new asymmetric centers are generated stereospecifically. Regiocontrol is also notable in the syntheses of **9** and **11**, inter alia.

Acknowledgment. We thank the National Science Foundation and the National Institutes of Health for their support of this work.

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(11) Both isomers can be successfully used in silicon-tethered 4 + 2 cycloadditions, e.g., to **1**.

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(13) Use of chlorosilyl rather than (dimethylamino)silyl derivatives is necessary when electrophilic olefins are involved to avoid conjugate addition of the dimethylamine released during silyl ether formation.

New Preparation of α-Methylene-γ-butyrolactones Mediated by (Iodomethyl)zinc Iodide

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A number of α-methylene-γ-butyrolactones display significant biological activity, and many syntheses of this class of molecules have been described.[2] We report a new stereoselective one-pot

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