Pyramidalization and Reactivity of Trigonal Centers. X-ray Crystal Structure Analysis of Two Silyl Enol Ethers from 1-Benzoyl- and 1-(Methoxycarbonyl)-2-*tert*-butyl-3,5-dimethyl-4-imidazolidinone (Reagents for Amino Acid Synthesis)

Dieter Seebach,* Thomas Maetzke,[1] Walter Petter, Bernhard Klötzer, and Dietmar A. Plattner

Contribution from the Laboratorium für Organische Chemie and the Institut für Kristallographie und Petrographie der Eidgenössischen Technischen Hochschule Zürich, ETH-Zentrum, Universitätstrasse 16, CH-8092 Zürich, Switzerland. *Received June 28, 1990*

Abstract: The title structures, which may be considered models for the Li enolates, contain three trigonal centers (N1, N3, C5) with unusually large pyramidalization. This leads to an all-trans arrangement of four substituents with respect to the plane of the five-membered ring which is in a flat twist conformation, bearing the *tert*-butyl group in a *quasi-axial-type* position. The pyramidalization on C5 is in the same direction from which this carbon undergoes electrophilic attack in reactions of the corresponding Li enolates.

Introduction

The importance of minimization of torsion in additions to trigonal centers has been recognized in the pioneering work on conformational analysis by Barton (A, B in Scheme I).[2] It was Schleyer who pointed out in 1967 that the unexpectedly high preference for exo over endo addition (C) to norbornene can be interpreted as a torsional effect.[3] A year later Felkin proposed to use this effect for discussing axial vs equatorial attack on cyclohexanones[4] (D). Johnson's concept of allylic strain as a decisive factor in stereoselective additions to double bonds is also based on a torsional effect[5] (E). Calculations by Anh,[6] Wipf,[7] and Houk[7] confirmed the importance of torsional contributions in these processes (F). By theoretical work[7,8] it was also found that a trigonal center pyramidalizes when put in an unsymmetrical environment. In the most simple case, the carbon atom next to the methyl group in conformation G of propane is pyramidalized as drawn.[7] Clearly, in an addition to the trigonal carbon atom of this conformation, minimalization of torsion will be attained on trajectory a, but not in an approach indicated by arrow b.[7] In turn, this leads to the prediction that the face of torsionally preferred attack on a double bond can be read from the pyramidalization in the reactive conformation, if only we knew it.[9]

Although there are numerous crystal structures exhibiting molecules with pyramidalized trigonal carbon atoms,[10,11] there was very little *experimental* evidence for the relationship between pyramidalization and reactivity in simple organic compounds containing common functional groups.[12,13] Two years ago, we noticed that the trigonal carbon atoms of dioxinones are slightly (α = 2–5°) pyramidalized as indicated in H (Scheme I).[9] In the Cambridge Structural Data Base (CSD) we found dozens of molecules in which such six-membered rings containing trigonal centers in "sofa" conformations showed the same effect.[14] The direction of pyramidalization coincides in the dioxinones with that

(1) Part of the Ph.D. Thesis of Th.M., NO. 9206, ETH, Zürich, 1990.

(2) Eliel, E. L. *Stereochemistry of Carbon Compounds*; McGraw-Hill: New York, 1962; pp 219–234. Fürst, A.; Plattner, P. A. *Abstracts of Papers of the 12th International Congress on Pure and Applied Chemistry*, New York; National Research Council: Washington, DC, 1951; p 409. Corey, E. J.; Sneen, R. A. *J. Am. Chem. Soc.* **1956**, *78*, 6269–6278.

(3) (a) Schleyer, P. v. R. *J. Am. Chem. Soc.* **1967**, *89*, 701–703. (b) Compare also Huisgen's factor *X*: Huisgen, R.; Ooms, P. H. J.; Mingin, M.; Allinger, N. L. *J. Am. Chem. Soc.* **1980**, *102*, 3951–3953.

(4) Chêrest, M.; Felkin, H.; Prudent N. *Tetrahedron Lett.* **1968**, 2199–2204. Chêrest, M.; Felkin, H. *Tetrahedron Lett.* **1968**, 2205–2208. Toromanoff, E. *Tetrahedron* **1980**, *36*, 2809–2931.

(5) Johnson, F. *Chem. Rev.* **1968**, 375–413. Hoffmann, R. W. *Chem. Rev.* **1989**, *89*, 1841–1860. Tomioka, K.; Kawasaki, H.; Yasuda, K.; Koga, K. *J. Am. Chem. Soc.* **1988**, *110*, 3597–3601. Birch, A. J.; Subba Rao, G. S. R. *Aust. J. Chem.* **1970**, *23*, 547–552.

(6) Anh, N. T.; Eisenstein, O. *Top. Curr. Chem.* **1980**, *88*, 145–162. Anh, N. T.; Eisenstein, O. *Nouv. J. Chim.* **1977**, *1*, 61–70.

(7) Wipf, G.; Morokuma, K. *Tetrahedron Lett.* **1980**, *21*, 4445–4448. Rondan, N. G.; Paddon-Row, M. N.; Caramella, P.; Houk, K. N. *J. Am. Chem. Soc.* **1981**, *103*, 2436–2438. Paddon-Row, M. N.; Rondan, N. G.; Houk, K. N. *J. Am. Chem. Soc.* **1982**, *104*, 7162–7166. Houk, K. N.; Rondan, N. G.; Brown, F. K.; Jorgensen, W. L.; Madura, J. D.; Spellmeyer, D. C. *J. Am. Chem. Soc.* **1983**, *105*, 5980–5988.

(8) Hake, H.; Landen, H.; Martin, H.-D.; Mayer, B.; Steigel, A.; Distefano, G.; Modelli, A. *Tetrahedron Lett.* **1988**, *29*, 6601–6604, and references to earlier papers cited therein.

(9) Seebach, D.; Zimmermann, J.; Gysel, U.; Ziegler, R.; Ha, T.-K. *J. Am. Chem. Soc.* **1988**, *110*, 4763–4772.

(10) The effect is especially strong in highly strained molecules; a collection of examples is found in: *Stereochemistry and Reactivity of Systems Containing π-Electrons*, proceedings of a symposium held in 1982, in honor of Prof. P. Bartlett; Watson, W. H., Ed.; Verlag Chemie International: Deerfield Beach, FL, 1983. Some more recent papers on the subject of pyramidalization in polycyclic structures are: Irngartinger, H.; Deuter, J.; Charumilind, P.; Paquette, L. A. *J. Am. Chem. Soc.* **1989**, *111*, 9236–9237, and earlier references cited therein. Gerson, F.; Qin, X.-Z.; Ess, C. *J. Am. Chem. Soc.* **1989**, *111*, 6456–6457, and references cited therein. For extreme pyramidalizations in dodecahedrenes see: Pinkos, R.; Melder, J.-P.; Prinzbach, H. *Angew. Chem.* **1990**, *102*, 102–105; *Angew. Chem., Int. Ed. Engl.* **1990**, *29*, 92–95. Melder, J.-P.; Pinkos, R.; Fritz, H.; Prinzbach, H. *Angew. Chem.* **1990**, *102*, 105–109; *Angew. Chem., Int. Ed. Engl.* **1990**, *29*, 95–99.

(11) In crystal structures containing enamine and amide moieties pyramidalizations of trigonal carbons are also seen: cf. references given in ref 9 and: Collins, T. J.; Uffelman, E. S. *Angew. Chem.* **1989**, *101*, 1552–1554; *Angew. Chem., Int. Ed. Engl.* **1989**, *28*, 1509–1511. For pyramidalizations in cp, cp* and benzene rings of transition-metal complexes see, for instance: Haaland, A. *Top. Curr. Chem.* **1975**, *53*, 1–23. Schultz, A. J.; Brown, R. K.; Williams, J. M.; Schrock, R. R. *J. Am. Chem. Soc.* **1981**, *103*, 169–176. Stollmaier, F.; Thewalt, U. *J. Organomet. Chem.* **1981**, *222*, 227–233. Bruck, M. A.; Copenhaver, A. S.; Wigley, D. E. *J. Am. Chem. Soc.* **1987**, *109*, 6525–6527. Hull, J. W., Jr.; Gladfelter, W. L. *Organometallics* **1982**, *1*, 1716–1718. For pyramidalizations in cyclophanes see, for instance: Cram, D. J.; Cram, J. M. *Acc. Chem. Res.* **1971**, *4*, 204–213. Misumi, S.; Otsubo, T. *Acc. Chem. Res.* **1978**, *11*, 251–256. Pyramidalization in 7-Phenyl-norbornenylium SbF_6^-: Laube, T. *J. Am. Chem. Soc.* **1989**, *111*, 9224–9232. In lithiated isopropylphenylsulfone Li is bonded to oxygen and the carbanionic carbon is strongly pyramidalized (Δ = 0.33 Å): Gais, H.-J.; Vollhardt, J.; Hellmann, G.; Paulus, H.; Lindner, J. *Tetrahedron Lett.* **1988**, *29*, 1259–1262.

(12) For a speculative proposal see: Stork, G.; Darling, S. D. *J. Am. Chem. Soc.* **1960**, *82*, 1512–1513. Stork, G., Darling, S. D. *J. Am. Chem. Soc.* **1964**, *86*, 1761–1768. Caine, D. *Org. React.* **1976**, *23*, 22.

(13) Burdisso, M.; Gamba, A.; Gandolfi, R.; Toma, L.; Rastelli, A.; Schiatti, E. *J. Org. Chem.* **1990**, *55*, 3311.

(14) The Cambridge Crystallographic Database, Cambridge Crystallographic Data Centre, University Chemical Laboratory, Lensfield Road, Cambridge CB2 1EW, England.

0002-7863/91/1513-1781$02.50/0 © 1991 American Chemical Society

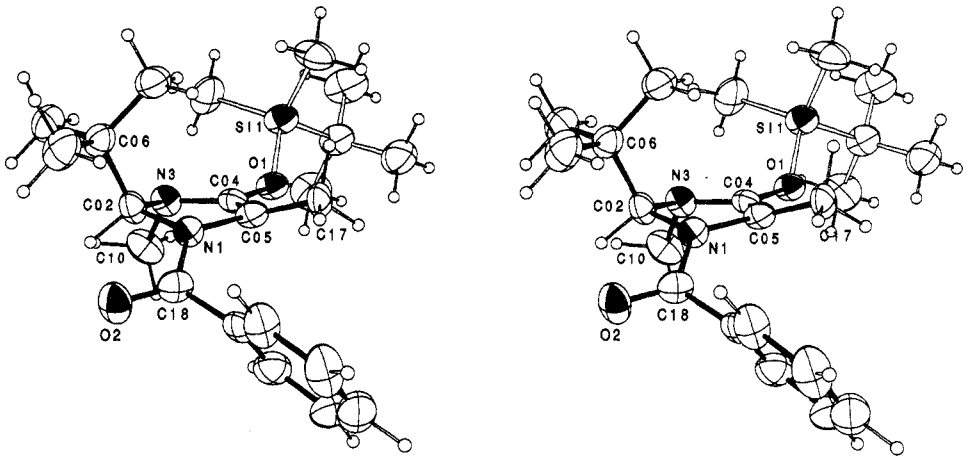


Figure 1. Stereo drawing (ORTEP) of the crystal structure of **2a**; the ellipsoids are drawn at the 30% level.

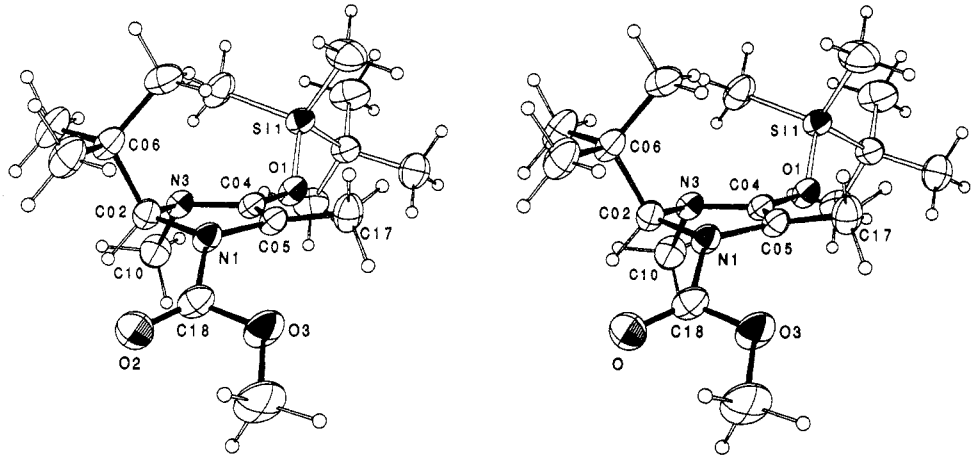


Figure 2. Stereo drawing (ORTEP) of the crystal structure of **2b**; the ellipsoids are drawn at the 30% level.

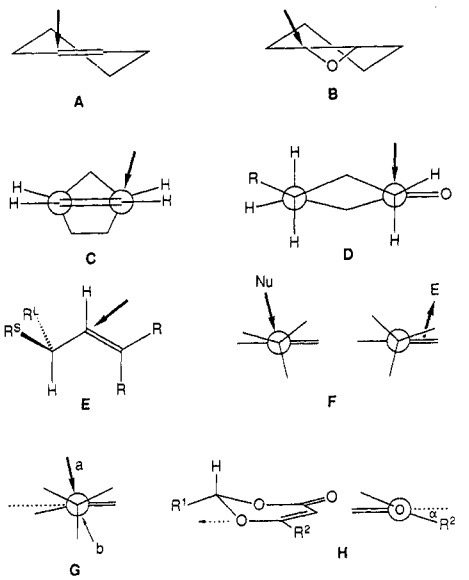
of nucleophilic attack and catalytic hydrogenation (relative topicity ul-1.3).[15] Most recently Ermer determined the crystal structure of norbornene dicarboxylic acid anhydride by neutron diffraction[16] and confirmed the calculational results of Wipf[7] and Houk[7] and thus, in a way, the original suggestion by Schleyer.[3a]

Crystal Structure of Two Imidazolidinone Silyl Enol Ethers

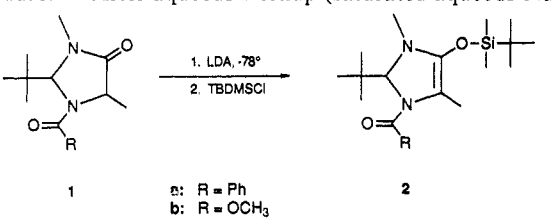
We now report the X-ray crystal structures of two silyl enol ethers with dramatic pyramidalizations of trigonal carbon atoms pointing in the same direction from which protonations occur and from which the corresponding Li enolates are generally approached with high diastereoselection by *all* kinds of electrophiles.[17,18]

The racemic imidazolidinones **1a** and **1b** were prepared by methylation of the corresponding precursors.[19-22] The enolates

Scheme I



were generated with LDA and O-silylated according to a known procedure.[23] After aqueous workup (saturated aqueous NaH-



(15) We explain this terminology herewith: *rel. topicity* is an unambiguous descriptor for the course of a diastereoselective reaction, *like* (lk) meaning *Re* approach to a trigonal center with respect to an *R* center present in the molecule (or *Si*/*S*), unlike (ul) referring to *Re* approach with respect to an *S* center (or *Si*/*R*). As the descriptors l (for *R,R* or *S,S*) and u (for *R,S* or *S,R*) specifying (*rel.*) *configurations*, lk und ul are reflection invariant. Seebach, D.; Prelog, V. *Angew. Chem.* **1982**, *94*, 696-702; *Angew. Chem., Int. Ed. Engl.* **1982**, *21*, 654-660.

(16) Ermer, O.; Bell, P.; Mason, S. A. *Angew. Chem.* **1989**, *101*, 1298-1301; *Angew. Chem., Int. Ed. Engl.* **1989**, *28*, 1239-1241.

(17) Seebach, D.; Naef, R. *Helv. Chim. Acta* **1981**, *64*, 2704-2708. Seebach, D.; Imwinkelried, R.; Weber, T. In *Modern Synthetic Methods*; Scheffold, R., Ed.; Springer: Berlin, 1986, Vol. 4, pp 125-260.

(18) Seebach, D.; Dziadulewicz, E.; Behrendt, L.; Cantoreggi, S.; Fitzi, R. *Liebigs Ann. Chem.* **1989**, 1215-1232.

(19) Fitzi, R.; Seebach, D. *Tetrahedron* **1988**, *44*, 5277-5292.

(20) Seebach, D.; Aebi, J. D.; Naef, R.; Weber, T. *Helv. Chim. Acta* **1985**, *68*, 144-154.

(21) Only the trans isomer of **2b** was formed (as determined by 200-MHz ^{1}H NMR spectroscopy of the crude product).

(22) Seebach, D.; Juaristi, E.; Miller, D. D.; Schickli, C.; Weber, T. *Helv. Chim. Acta* **1987**, *70*, 237-261.

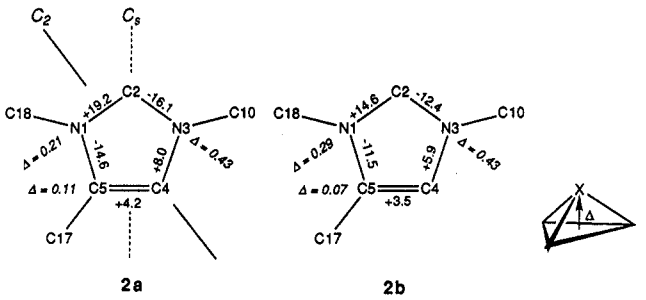


Figure 3. Torsion angles (degrees) in the five-membered ring of **2a** and **2b** and definition of pyramidalization Δ (angstroms).

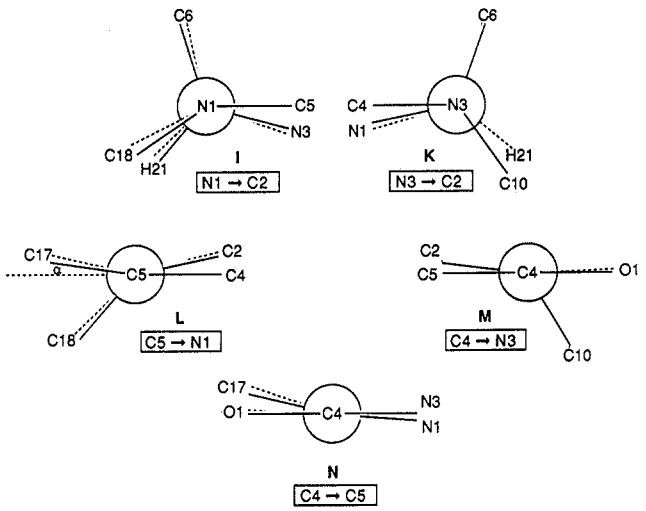


Figure 4. Newman projections about the bonds in the five-membered ring of **2a** (dotted lines, if different from **2b**); in each projection one horizontal bond is common to both structures of **2a** and **2b**.

CO_3), the silyl enol ethers were recrystallized under argon several times (pentane) to give colorless crystals that were used for the X-ray structure analysis (see Experimental Section).

The structures of the two silyl enol ethers are very similar to each other so they are described together.

The five-membered ring deviates little from planarity. The puckering amplitude according to Cremer and Pople[24] is q = 0.18 Å (**2a**) and q = 0.14 Å (**2b**) (puckering amplitude in cyclopentane: q = 0.281 Å). The phase angle is ϕ = 23.8° (**2a**) and ϕ = 23.3° (**2b**). In both structures these values are by $\Delta\phi$ = 5.8° (**2a**) and $\Delta\phi$ = 5.3° (**2b**) closer to the phase angle of a twist form (ϕ = 18°, 54°, 90°, ...) than that of an envelope (ϕ = 0°, 36°, 72°, ...) with $\Delta\phi$ = 12.2° (**2a**) and $\Delta\phi$ = 12.7° (**2b**). Therefore, the conformation of the five-membered ring resembles a twist form (C_2 symmetry) rather than an envelope (C_s symmetry).[25] This result is confirmed by the pattern of the torsion angles in the five-membered ring, which fits better to C_2 symmetry (see Figure 3) than to C_s symmetry.

The *tert*-butyl group has a *pseudo-axial*-type position; the nitrogen N1 of the exocyclic amide (**2a**) and of the carbamate group (**2b**) is strongly pyramidalized (see Figure 3). The pyramidalization of the nitrogen N3 is similar to that in tertiary amines[26] [torsion angle C5–C4–N3–C10 = −119.4° (**2a**), −121.6° (**2b**)], with the methyl group lying also below the plane through the five-membered ring. This leads to a nearly eclipsed conformation of the substituents at N1 and N3 with the C2–H bond

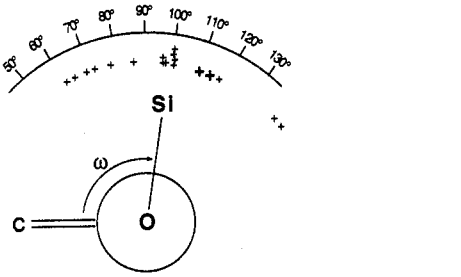


Figure 5. Torsion angles about the C–O bond in the 11 crystal structures of silyl enol ethers of the CSD;[27] **2a** and **2b** are marked with bold crosses. (In some of the represented structures there is more than one silyl enol ether moiety.)

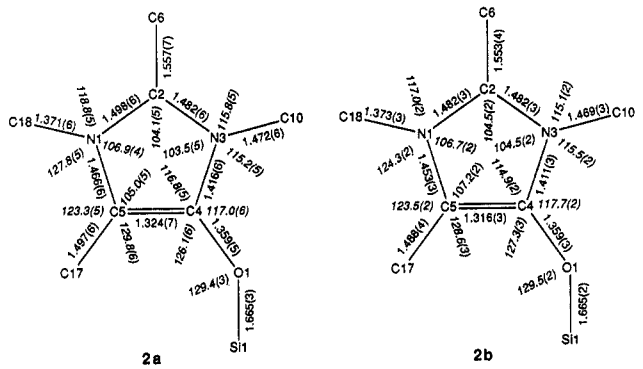


Figure 6. Bond lengths (angstroms) and angles (degrees) of **2a** and **2b** (standard deviations in parentheses).

(see I and K in Figure 4). The trigonal center C4 is planar within the standard deviation. The other trigonal center, C5, however, is strongly pyramidalized in the direction opposite to that of pyramidalization N1 and N3 so that the methyl group lies above the plane through the five-membered ring [torsion angle N3–C4–C5–C17 = −160.5° (**2a**), −166.5° (**2b**)]. The angle α between the bond vector C5–C17 and the plane N1–C5–C4 is 11.7° in **2a** and 7.8° in **2b** (see L in Figure 4). The O–Si bond is turned out of the plane of the double bond by 110° in **2a** and by 114° in **2b** (see the comparison of the 11 crystal structures[27] of silyl enol ethers in the CSD in Figure 5).

The length of the enol double bond (see Figure 6) is slightly shorter than in Li enolates (1.34 Å, mean value) and enamines (1.34 Å, mean value).[28] The N3–C4 distance corresponds to enamines with a similar pyramidalization at the nitrogen (in enamines this distance correlates with the pyramidality of the nitrogen).[28] The C5–N1 bond length is about 0.04 Å longer than in enamines[28] (compare with C4–N3) and than one would expect for an sp^2-hybridized carbon atom.[29] In contrast, the $C5_{sp^2}$–$C17_{sp^3}$ distance corresponds to the expected value (1.50 Å[29]). The N1–C2 and C2–N3 distances are slightly longer than in comparable heterocyclic species and are even longer than that seen in tertiary amines (1.47 Å). Although the distance N1–C18 is slightly longer than in common amides (1.35 Å[29]), it is similar to corresponding *N,N*- and *N,O*-acetals attached to such protecting groups.

As was observed in ester[30] and amide[26] enolates earlier, the angle C5–C4–O1 is larger than N3–C4–O1 by about 10°. Also, the

(23) Rathke, M. W.; Sullivan, D. F. *Synth. Commun.* **1973**, *3*, 67. Modified procedure according to: Colvin, E. W. *Silicon Reagents in Organic Chemistry*; Academic Press: New York, 1988; p 101.

(24) Cremer, D.; Pople, J. A. *J. Am. Chem. Soc.* **1975**, *97*, 1354–1358.

(25) Dunitz, J. D. *X-Ray Analysis and the Structure of Organic Molecules*; Cornell University Press: Ithaca, NY, 1979.

(26) In amide Li enolates the nitrogen is completely "tetrahedralized": Laube, T.; Dunitz, J. D.; Seebach, D. *Helv. Chim. Acta* **1985**, *68*, 1373–1393. Bauer, W.; Laube, T.; Seebach, D. *Chem. Ber.* **1985**, *118*, 764–773.

(27) Short-form references to individual CSD entries: BOPTIJ: *Angew. Chem., Int. Ed. Engl.* **1983**, *22*, 61. BPOXSH: *Acta Crystallogr. Sect. B* **1976**, *32*, 930–932. COZPOW: *Angew. Chem., Int. Ed. Engl.* **1984**, *23*, 635–637. CURLAC: *Acta Chem. Scand. Ser. B* **1985**, *39*, 7–13. DIWXOW: *Helv. Chim. Acta* **1985**, *68*, 264–282. DORKIE: *J. Org. Chem.* **1986**, *51*, 2408–2416. DOYFOM: *J. Chem. Soc., Chem. Commun.* **1986**, 1116–1118. DUNRUZ: *Can. J. Chem.* **1986**, *64*, 739–743. FODREV: *Organometallics* **1987**, *6*, 1246–1256. FUVXUP: *J. Chem. Soc., Chem. Commun.* **1988**, 72–74. SIXCED: *Acta Chem. Scand. Ser. A* **1977**, *31*, 641–644.

(28) Brown, K. L.; Damm, L.; Dunitz, J. D.; Eschenmoser, A.; Hobi, R.; Kratky, C. *Helv. Chim. Acta* **1978**, *61*, 3108–3135.

(29) Allen, F. H.; Kennard, O.; Watson, D. G.; Brammer, L.; Orpen, A. G.; Taylor, R. *J. Chem. Soc., Perkin Trans. 2* **1987**, S1–S19.

(30) Seebach, D.; Amstutz, R.; Laube, T.; Schweizer, W. B.; Dunitz, J. D. *J. Am. Chem. Soc.* **1985**, *107*, 5403–5409.

angle C18–N1–C5 is significantly larger than C18–N1–C2 (see Figure 6). Additionally, it is conspicuous that the *endocyclic* angle N3–C4–C5 is significantly larger than the one at the trigonal sp^2 carbon atom C5 (N1–C5–C4) and the other three angles in the five-membered ring which are all smaller than 108°!

Discussion of the Results

The structures of the two silyl enol ethers **2a** and **2b** have three remarkable features: (a) The *tert*-butyl group at the acetal carbon atom C2 is in a pseudo-axial-type disposition on the five-membered ring. (b) The trigonal center C5 is strongly pyramidalized. (c) The amide (enamine) nitrogen N1 is pyramidalized, and the enamine nitrogen N3 is completely "tetrahedralized" (sp^3-hybridized N).

The strong pyramidalization at N1 puts the acyl group and the *tert*-butyl group on opposite sides of the five-membered ring. This effect is also observed in the starting material as was shown by X-ray crystal structure analysis.[31-33] The pyramidalizations at the enamine nitrogen N3 and at the trigonal carbon atom C5, however, are probably not a consequence of steric interactions: On one hand, the angular strain within the five-membered ring is minimized by pyramidalizations, and on the other hand, it is known that an enamine-like nitrogen in amide enolates is almost completely tetrahedralized.[26] The pyramidalization at the trigonal carbon atom C5 is most likely a consequence of stereoelectronic effects. The enol double bond is connected to three heteroatom substituents bearing electron lone pairs. Therefore, one could interpret the pyramidalization at C5 as a consequence of the enhanced electron density on the upper side of the five-membered ring caused by the lone pairs of the nitrogen atoms. In the crystal structure of the 11 silyl enol ethers of the CSD, no pyramidalization was observed at the carbon atom β to oxygen. This points to no stereoelectronic contribution from the O–Si bond, although the torsion angles about the C–O bond are all in the range from 60° to 120° (see Figure 5).

One hydrogen atom at C17 in the carbamate **2b** has van der Waals contact (O···H–C17 = 2.4 Å) with the oxygen of the methoxy group (torsion angle C5–N1–C18–O3 = 27.3°). The corresponding methyl group in **2a** has also van der Waals contact to the phenyl group; however, the hydrogen positions in this crystal structure are calculated (the distance of C17 from the plane of the phenyl ring is 3.1 Å; torsion angles C5–N1–C18–C19 = 10.7, N1–C18–C19–C20 = −72.1°).

The proximity of the phenyl group in **2a** to the pathway of an electrophile in its attack of the nucleophilic center C5 could account for the earlier observed substituent effects of the phenyl ring on the stereoselectivity in such alkylation reactions.[22,34] The higher selectivity of the benzyloxy- and *tert*-butoxycarbonyl-substituted imidazolidinone and oxazolidinone enolates as compared with the selectivity of the corresponding benzoyl derivatives[17-19,31a,35] is probably caused by the fact that the carbonyl carbon bears a smaller substituent in the former case. There is much less steric hindrance for electrophilic attack from the bottom side of the five-membered ring in **2b** (torsion angle N1–C18–O3–C19 = 179.5°). The X-ray crystal structure also shows that the *tert*-butyl group is shielding one side of the five-membered ring (see Figure 7), which plays a dominant role in achieving the high diastereoselectivities observed in the alkylation reactions.

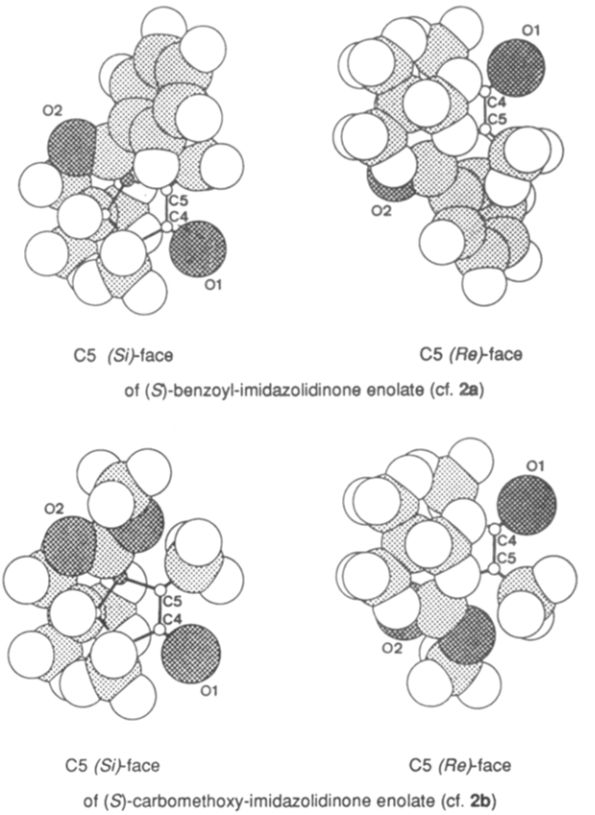


Figure 7. Space-filling models of **2a** (top) and **2b** (bottom) with both views perpendicular to the plane N1–C5–C4–N3 of the five-membered ring. (The radii are drawn at 70% of the van der Waals radii; the atoms within the five-membered ring are drawn as small spheres.)

Finally, we should comment on whether it is justified to compare the structure of a lithium enolate with that of a silyl enol ether.[36] The phenomenon of aggregation of organolithium compounds in solution and in the solid state[37] is of course not found with silyl enol ethers. However, we think that it is unlikely that there are dramatic structural differences in the heterocyclic five-ring unit of a Li enolate and the silyl enol ether. As to the structure of the enolate moiety, the following arguments should be mentioned: (a) The pyramidalization in the Li enolates could be even larger, as there could be a higher partial negative charge at the α-carbon atom C5. (b) The O–Si bond is turned out of the plane of the double bond as is the case for the O–Li bond in the corresponding Li enolates. (c) Protonation of the silyl enol ether **2b** by workup with 1 N HCl or by quenching of a solution of **2b** with TFA gives exclusively the cis diastereoisomer. This is also the case for the corresponding Li enolate when its THF solution is quenched with acetic acid at −70° C (see Experimental Section).

The results presented here demonstrate how delicate the factors determining the selectivity of a reaction may be! They represent another case in which the stereoselectivities of a reaction of a common reagent can be correlated with a pyramidalization in the solid state.

Experimental Section

General. Merck Kieselgel 60 (silica, mesh size 0.040–0.064) was used for flash chromatography. The infrared spectra (IR) were recorded on

(31) (a) Weber, T.; Aeschimann, R.; Maetzke, T.; Seebach, D. *Helv. Chim. Acta* **1986**, *69*, 1365–1377. (b) Seebach, D.; Jeanguenat, A.; Schmidt, J.; Maetzke, T. *Chimia* **1989**, *43*, 314–317. (c) Unpublished results; X-ray crystal structures of (2*S*,5*S*,1′*S*)-2-*tert*-butyl-1-(*tert*-butyloxycarbonyl)-3-methyl-5-(nitroprop-2-yl)-4-imidazolidinone: Fitzi, R. Ph.D. Thesis No. 8654, ETH, Zürich, 1988. (2*R*,4*R*,5*R*)-2-*tert*-butyl-4-hydroxy-3-(methoxycarbonyl)-5-(2′-oxo-2′-phenylethyl)-1,3-oxazolidine: Stucky, G. Ph.D. Thesis No. 8904, ETH, Zürich, 1989.

(32) In a crystal structure with two molecules in the asymmetric unit quite different pyramidalizations occur: Egli, M.; Polt, R.; Seebach, D. *Chimia.* **1989**, *43*, 4–5.

(33) In corresponding six-membered ring *N,N*-acetals (with a tertiary butyl group at the acetal center) only very small pyramidalizations occur as there is almost no strain. Unpublished results of three X-ray crystal structure analyses; 1-benzoyl-2-*tert*-butyl-3-methylperhydropyrimidin-4-one: Lamatsch, B. 1-Benzoyl-5-benzyl-2-*tert*-butyl-3-methylperhydropyrimidin-4-one: Hidber, P.; Maetzke T. 1-Benzoyl-5-bromo-6-(bromomethyl)-2-*tert*-butyl-3-methyl-perhydropyrimidin-4-one: Lamatsch, B. All ETH Zürich 1989/1990.

(34) Compare also: Evans, D. A.; Chapman, K. T.; Bisaha, J. *J. Am. Chem. Soc.* **1988**, *110*, 1238–1256.

(35) Seebach, D.; Fadel, A. *Helv. Chim. Acta* **1985**, *68*, 1243–1250. Seebach, D.; Müller, S. G.; Gysel, U.; Zimmermann, J. *Helv. Chim. Acta* **1988**, *71*, 1303–1318.

(36) Many attempts were made to recrystallize the crystalline powders of the Li enolates but it was impossible to get suitable single crystals for X-ray crystal structure analysis.

(37) Review article: Seebach, D. *Angew. Chem.* **1988**, *100*, 1685–1715; *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 1624–1654.

a Perkin–Elmer 782 infrared spectrophotometer; the position of the absorption maxima is given in cm^{-1}. Nuclear magnetic resonance (NMR) spectra were obtained on a Bruker WM-300, a Varian EM 390 (90 MHz), and a Varian Gemini (200 MHz) spectrometer in $CDCl_3$; the chemical shifts are given in δ values relative to TMS as an internal standard. Mass spectra were obtained with a VG-TRIBRID (CI, 70 eV) mass spectrometer.

2-*tert*-Butyl-1-(methoxycarbonyl)-3-methylimidazolidin-4-one. To a stirred solution of 2-*tert*-butyl-3-methylimidazolidin-4-one[38] (15.0 g, 96.0 mmol) and triethylamine (21.1 mL, 151 mmol) in 120 mL of CH_2Cl_2 was added methyl chloroformate (11.1 mL, 144 mmol) at 0 °C. The solution was stirred for 30 min at this temperature, and then water was added and the aqueous layer was extracted with CH_2Cl_2. The combined extracts were washed twice with 1 N HCl and twice with saturated aqueous $NaHCO_3$ and brine and dried ($MgSO_4$), and the solvent was removed by rotary evaporation. The crude product was recrystallized from hexane/*tert*-butyl methyl ether to give 2-*tert*-butyl-1-(methoxycarbonyl)-3-methylimidazolidin-4-one (11.3 g, 55%) as a white solid: mp 135.5 °C; IR ($CHCl_3$) 2870 (m), 1700 (s), 1450 (m), 1400 (m), 1380 (s), 1303 (m), 1254 (m), 1112 (m), 1030 (w), 1003 (w), 974 (m); ^1H NMR ($CDCl_3$, 90 MHz) 4.93 [s, 1 H, C(2)–H], 4.13 [AB, J = 16 Hz, 1 H, C(5)–H], 3.73 [AB, J = 16 Hz, 1 H, C(5)–H], 3.71 (s, 3 H, OCH_3), 2.97 (s, 3 H, NCH_3), 0.98 (s, 9 H, *t*-Bu); ^{13}C NMR (75 MHz) 170.2, 156.0, 82.8, 53.1, 49.7, 39.6, 31.6, 25.9; MS; m/z 429 (M_2H^+, 9), 216 (12), 215 (MH^+, 65), 158 (27), 157 (100), 88 (24), 44 (20), 42 (20). Anal. Calcd for $C_{10}H_{18}N_2O_3$: C, 56.06; H, 8.47; N, 13.07. Found: C, 56.11; H, 8.56; N, 13.08.

***trans*-2-*tert*-Butyl-1-(methoxycarbonyl)-3,5-dimethylimidazolidin-4-one (*trans*-1b).** Lithium diisopropylamide (LDA) was generated from *n*-BuLi (22.5 mL of a 1.6 M solution in hexane, 36.0 mmol) and diisopropylamine (5.6 mL, 39.5 mmol) in 50 mL of THF at −10 °C for 15 min. 2-*tert*-Butyl-1-(methoxycarbonyl)-3-methylimidazolidinone was dissolved in 40 mL of THF and added dropwise to the LDA solution at −78 °C to generate the colorless enolate, which was stirred for 1 h at −78 °C. Methyl iodide (2.3 mL, 36.9 mmol) was added, and the stirred solution was allowed to warm to room temperature. The solvent was removed by rotary evaporation, and the residue was dissolved in ether. The solution was washed twice with 1 N HCl and twice with saturated aqueous $NaHCO_3$, brine and dried ($MgSO_4$). Solvent removal by rotary evaporation yielded a crude product which was purified by flash chromatography (eluant ethyl acetate/hexane 4:1) and recrystallized from hexane to give *trans*-**1b** (4.6 g, 62%) as colorless crystals: mp 82.0–82.5 °C; IR ($CHCl_3$) 2968 (m), 1700 (s), 1481 (m), 1451 (s), 1407 (m), 1400 (m), 1380 (s), 1318 (m), 1298 (m), 1139 (m), 1124 (m), 1057 (w), 1035 (m), 1008 (w), 887 (w); ^1H NMR (200 MHz) 5.03 [s, 1 H, C(2)–H], 4.04 [q, J = 6.8 Hz, 1 H, C(5)–H], 3.73 (s, 3 H, OCH_3), 3.02 (s, 3 H, NCH_3), 1.56 [d, J = 6.8 Hz, 3 H, C(5)–CH_3], 0.97 (s, 9 H, *t*-Bu); NOE measurements irradiation, 0.97 → positive NOE 4.04; ^{13}C NMR (75 MHz) 172.8, 154.5, 81.0, 55.7, 52.2, 40.5, 32.0, 26.3, 17.4; MS, m/z 457 (M_2H^+, 14), 230 (16), 229 (MH^+, 75), 197 (11), 172 (39), 171 (100), 112 (15), 102 (33), 58 (40), 42 (21). Anal. Calcd for $C_{11}H_{20}N_2O_3$: C, 57.87; H, 8.83; N, 12.27. Found: C, 57.88; H, 8.75; N, 12.32.

***cis*-2-*tert*-Butyl-1-(methoxycarbonyl)-3,5-dimethylimidazolidin-4-one (*cis*-1b).** Lithium diisopropylamide (LDA) was generated from *n*-BuLi (1.4 mL of a 1.6 M solution in hexane, 2.2 mmol) and diisopropylamine (0.35 mL, 2.5 mmol) in 5 mL of THF at −10 °C for 15 min. Imidazolidinone *trans*-**1b** (0.458 g, 2.01 g) was dissolved in 10 mL of THF and added dropwise to the LDA at −78 °C to generate the colorless enolate, which was stirred for 1 h at this temperature. A second 1.1 equiv of *n*-BuLi was added, and the solution was stirred for a further 20 min. The reaction mixture was quenched at −78 °C with a solution of acetic acid (0.5 mL, 8.7 mmol) in THF (1 mL) and warmed to room temperature. The solvent was removed by rotary evaporation, and the residue was dissolved in ether. The solution was washed three times with saturated aqueous $NaHCO_3$ and brine and dried ($MgSO_4$). The solvent was removed to give *cis*-**1b** (0.426 g, 93%) as a colorless, viscous oil which was pure according to the ^1H NMR analysis: IR ($CHCl_3$) 2978 (m), 1698 (s), 1481 (m), 1443 (s), 1400 (m), 1364 (s), 1340 (m), 1295 (m), 1140 (w), 1128 (w), 1118 (w), 1088 (w), 1061 (w), 1034 (w), 1009 (w), 888 (w); ^1H NMR (200 MHz) 4.99 [s, 1 H, C(2)–H], 4.19 [q, J = 7.0 Hz, 1 H, C(5)–H], 3.76 (s, 3 H, OCH_3), 2.99 (s, 3 H, NCH_3), 1.49 [d, J = 7.0 Hz, 3 H, C(5)–CH_3], 1.00 (s, 9 H, *t*-Bu); ^{13}C NMR (75 MHz) 172.2, 157.2, 82.4, 56.2, 53.0, 37.6, 31.5, 26.5, 17.8.

1-Benzoyl-2-*tert*-butyl-3,5-dimethyl-4-[(*tert*-butyldimethylsilyl)oxy]-Δ4-imidazoline (2a). Lithium diisopropylamide (LDA) was generated from *n*-BuLi (2.44 mL of a 1.6 M solution in hexane, 4.00 mmol), diisopropylamine (0.62 mL, 4.40 mmol), and HMPT (0.70 mL, 3.98 mmol) in 5 mL of THF at −10 °C for 15 min. Imidazolidinone[38a] **1a** (1.046 g, 3.81 mmol) was dissolved in 10 mL of THF and added dropwise to the LDA solution at −78 °C to generate the orange enolate, which was stirred for 1 h at this temperature. A solution of *tert*-butyldimethylchlorosilane (TBDMSCl) (4.22 mL of a 1 M solution in hexane, 4.22 mmol) was added dropwise, and the reaction mixture was warmed to room temperature over a period of 2 h. The solvent was removed by rotary evaporation, and the yellow residue was dissolved in ether/pentane (1:1). The solution was washed four times with saturated aqueous $NaHCO_3$ and dried ($MgSO_4$) and the solvent removed by rotary evaporation. The crude crystalline product **2a** (1.4 g) was recrystallized three times from pentane under argon (by cooling from 36 °C to room temperature) to give colorless crystals: mp 98–100 °C; IR ($CHCl_3$) 2957 (s), 2860 (m), 1704 (m), 1620 (s), 1600 (s), 1461 (m), 1446 (m), 1427 (m), 1390 (s), 1297 (m), 1160 (m), 1135 (m), 1078 (m), 939 (w), 902 (m), 870 (s), 840 (m); ^1H NMR (200 MHz) 7.45–7.30 (m, 5 H, aromatic H), 5.01 [s, 1 H, C(2)–H], 2.60 (s, 3 H, NCH_3), 1.16 [s, 3 H, C(5)–CH_3], 0.96 (s, 9 H, *t*-Bu), 0.94 (s, 9 H, *t*-Bu), 0.26 (s, 3 H, Si–CH_3), 0.13 (s, 3 H, Si–CH_3); ^{13}C NMR (50 MHz) 172.1, 146.1, 138.2, 129.5, 128.1, 127.4, 100.2, 85.1, 39.6, 38.5, 25.2, 24.8, 17.7, 11.7, −4.1, −4.7.

X-ray Crystal Structure Analysis of $C_{22}H_{36}N_2O_2Si$ (2a). A crystal (0.3 × 0.4 × 0.4 mm) was fixed under nitrogen (glovebag) in a capillary (i.d. = 0.5 mm) with a glass fiber and mounted on a Syntex-$P2_1$ four-circle diffractometer. Monoclinic, space group $P2_1/c$ with a = 17.668(3) Å, b = 8.139(2) Å, c = 18.484(4) Å, β = 113.56(1)°, V = 2436 Å^3, M = 388.63, Z = 4, D_{calcd} = 1.06 g cm^{-3}, μ = 0.81 cm^{-1}, $F(000)$ = 848. Data were collected at 24 °C by using Mo Kα radiation (λ = 0.7107 Å) in the 2θ range of 3–50°. Intensities of 4452 independent reflections were measured and 1941 considered as observed with $I > 3\sigma(I)$ and used for the refinement. Absorption corrections were not applied. The structure was solved by direct methods (SHELXS-86[39]). All non-hydrogen atoms were refined anisotropically. Hydrogen atoms were refined in accordance to the riding model with idealized geometry (SHELX-76[40]). A total of 280 parameters were refined, and a weighting scheme ($w^{-1} = \sigma^2 F_o$) was used. The final values for R and R_w were 0.067 and 0.050, respectively, with the final Fourier difference map showing a maximum of 0.31 and a minimum of −0.26 e Å^{-3}.

2-*tert*-Butyl-1-(methoxycarbonyl)-3,5-dimethyl-4-[(*tert*-butyldimethylsilyl)oxy]-Δ4-imidazoline (2b). Lithium diisopropylamide (LDA) was generated from *n*-BuLi (3.0 mL of a 1.6 M solution in hexane, 4.80 mmol), diisopropylamine (0.75 mL, 5.3 mmol), and HMPT (0.84 mL, 4.80 mmol) in 8 mL of THF at −10 °C for 15 min. Imidazolidinone **1b** (0.997 g, 4.37 mmol) was dissolved in 10 mL of THF and added dropwise to the LDA at −78 °C to generate the colorless enolate, which was stirred for 1 h at this temperature. A solution of *tert*-butyldimethylchlorosilane (TBDMSCl) (4.90 mL of a 1 M solution in hexane, 4.90 mmol) was added dropwise, and the reaction mixture was warmed to room temperature over a period of 4 h. The solvent was removed by rotary evaporation, and the almost colorless residue was dissolved in ether/pentane (1:1). The solution was washed four times with saturated aqueous $NaHCO_3$ and dried ($MgSO_4$) and the solvent removed to give **2b** as a white crystalline solid (1.48 g) which was pure according to ^1H NMR analysis. The crude crystalline product was recrystallized three times from pentane (by cooling from +24 to −50 °C in 22 h) to give colorless prisms: mp 67.0–70.5 °C; IR ($CHCl_3$) 2955 (m), 2880 (m), 1692 (s), 1445 (s), 1365 (s), 1282 (m), 1120 (m), 1074 (m), 1034 (w), 1008 (w), 989 (w), 907 (m), 883 (m), 838 (m); ^1H NMR (200 MHz) 4.39 [s, 1 H, C(2)–H], 3.70 (s, 3 H, OCH_3), 2.50 (s, 3 H, NCH_3), 1.91 [s, 3 H, C(5)–CH_3], 0.97 (s, 9 H, *t*-Bu), 0.87 (s, 9 H, Si–*t*-Bu), 0.25 (s, 3 H, Si–CH_3), 0.14 (s, 3 H, Si–CH_3); ^{13}C NMR (50 MHz) 159.3, 145.2, 100.1, 86.8, 52.3, 39.9, 37.8, 25.5, 24.6, 18.0, 11.4, −3.8, −4.4.

X-ray Crystal Structure Analysis of $C_{17}H_{34}N_2O_3Si$ (2b). A crystal (0.4 × 0.4 × 0.4 mm) was fixed under nitrogen (glovebag) in a capillary (i.d. 0.5 mm) with an epoxy adhesive (Araldit, Ciba-Geigy) and mounted on a Picker-Stoe four-circle diffractometer. Monoclinic, space group $P2_1/c$ with a = 15.181(8) Å, b = 7.475(4) Å, c = 18.739(9) Å, β = 90.25(3)°, V = 2126.4 Å^3, M = 342.56, Z = 4, D_{calcd} 1.07 g cm^{-3}, μ = 0.92 cm^{-1}, $F(000)$ = 752. Data were collected at 24 °C by using Mo Kα radiation (λ = 0.7107 Å) in the 2θ range of 3–45°. Intensities of 2708 independent reflections were measured and 2142 considered as observed with $I > 3\sigma(I)$ and used for the refinement. Absorption corrections were not applied. The structure was solved by direct methods (SHELXS-86[39]). All non-hydrogen atoms were refined anisotropically. The hydrogen atoms

(38) (a) Naef, R.; Seebach, D. *Helv. Chim. Acta* **1985**, *68*, 135–143. (b) Fitzi, R.; Seebach, D. *Angew. Chem.* **1986**, *98*, 363–364; *Angew. Chem., Int. Ed. Engl.* **1986**, *25*, 345–346.

(39) Sheldrick, G. M. SHELXS-86, program for the solution of crystal structures; University of Göttingen, Germany, 1986.

(40) Sheldrick, G. M. SHELX-76, program for crystal structure determination; University of Cambridge, England, 1976.

could be located by a difference Fourier map and were refined isotropically; some hydrogen atoms were substituted by calculated H atom positions and refined in accordance to the riding model with idealized geometry (SHELX-76[40]). A total of 281 parameters were refined and a weighting scheme ($w^{-1} = \sigma^2 F_o$) was used. The final values for R and R_w were 0.039 and 0.040, respectively, with the final Fourier difference map showing a maximum of 0.14 and a minimum of -0.20 e Å^{-3}. The crystallographic figures were prepared with PLUTO[13] and ORTEP.[41]

Hydrolysis of the Silyl Enol Ether 2b with 1 N HCl. A sample of silyl enol ether **2b** (about 0.2 g) was dissolved in 30 mL of ether and shaken with 1 N HCl. The ether phase was washed twice with saturated aqueous $NaHCO_3$ and brine and dried ($MgSO_4$). Removal of the solvent by rotary evaporation yielded *cis*-**1b** as a colorless viscous oil which was pure by ^{1}H NMR analysis.

Acknowledgment. We gratefully acknowledge financial support by the Schweizerische Nationalfonds zur Förderung der Wissenschaftlichen Forschung (Grant 20-25276.88). Stipends have been supplied by Stipendienfonds der Basler Chemischen Industrie zur Unterstützung von Doktoranden auf dem Gebiete der Chemie (to Th.M), Sandoz AG (to D.A.P.), and Hoffmann-La Roche AG (Basel) (to B.K.).

Supplementary Material Available: Tables listing the atomic coordinates and thermal parameters, bond lengths, bond angles, and torsion angles (9 pages). Ordering information is given on any current masthead page.

(41) Johnson, C. K. ORTEP-II. Report ORNL-5138, Oak Ridge National Laboratory, Oak Ridge, TN, 1976.

Stereochemical Effects on the Mechanism of the Ozonolysis of (*E*)- and (*Z*)-*o*-(2-Phenyl-3-methoxy-2-propenyl)benzophenone

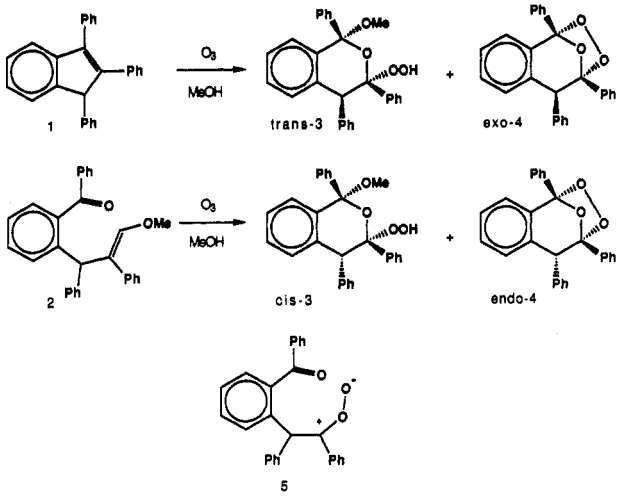
Kevin J. McCullough,*[1a] Norinaga Nakamura,[1b] Tomohiro Fujisaka,[1b] Masatomo Nojima,*[1b] and Shigekazu Kusubayashi[1b]

Contribution from the Department of Chemistry, Heriot-Watt University, Riccarton, Edinburgh EH14 4AS, Scotland, and Department of Applied Chemistry, Faculty of Engineering, Osaka University, Suita, Osaka 565, Japan. *Received August 10, 1990*

Abstract: The ozonolyses of (*E*)- and (*Z*)-*o*-(2-phenyl-3-methoxy-2-propenyl)benzophenone (**6**), which should proceed through a common carbonyl oxide intermediate **15**, afforded distinctly different reaction product mixtures, suggesting that the substrate stereochemistry exerts an influence on the overall reaction mechanism: (a) The reaction of (*E*)-**6** in carbon tetrachloride resulted in the formation of unidentified polymeric products, whereas 2,3-diphenylindene ozonide (**8**) was the major reaction product in acetic acid and methanol at 0 °C. From the ozonolysis of the isomeric keto olefin (*Z*)-**6** in both the protic and aprotic solvents, however, the ozonide **8** was obtained almost quantitatively. (b) The reaction of (*E*)-**6** in methanol–methylene chloride at -70 °C gave the methoxy hydroperoxide **9** in 81% yield, whereas the reaction of (*Z*)-**6** under similar conditions led to the formation of the hemiperacetal **10** (14% yield) together with the ozonide **8** (49% yield). Moreover, the high degree of similarity in the nature and distribution of the products from the ozonolyses of keto olefin (*Z*)-**6** and 2,3-diphenylindene (**7**) would be consistent with their respective reactions proceeding predominantly through a common carbonyl oxide intermediate.

The mechanism of the reaction of ozone with alkenes continues to attract considerable attention.[2] During our continuing study of the ozonolysis of indene derivatives,[3] it has been found that the reaction of 1,2,3-triphenylindene (**1**) with ozone in methanol–methylene chloride at -70 °C is highly stereoselective, resulting in the formation of the methanol-derived product *trans*-**3**, in which the phenyl group at the 2-position and the hydroperoxy group at the 1-position are trans-α related (Scheme I), together with the

Scheme I



ozonide *exo*-**4**. Conversely, the stereoisomeric methanol-derived product and ozonide, *cis*-**3** and *endo*-**4**, respectively, are exclusively obtained from the related keto olefin **2** (Scheme I).[4] Since both reactions formally proceed through the carbonyl oxide intermediate

(1) (a) Heriot-Watt University. (b) Osaka University.

(2) (a) Bailey, P. S. *Ozonation in Organic Chemistry*; Academic Press: New York, 1978; Vol. 1, 1982; Vol. 2, (b) Kuczkowski, R. L. In *1,3-Dipolar Cycloaddition Chemistry*; Padwa, A., Ed.; Wiley: New York, 1984; Vol. 2. (c) Pryor, W. A.; Giamalva, D.; Church, D. F. *J. Am. Chem. Soc.* **1985**, *107*, 2793. (d) Griesbaum, K.; Volpp, W.; Greinert, R. *Ibid.* **1985**, *107*, 5309. (e) Nakamura, N.; Nojima, M.; Kusabayashi, S. *Ibid.* **1987**, *109*, 4969. (f) Mori, M.; Nojima, M.; Kusabayashi, S. *Ibid.* **1987**, *109*, 4407. (g) LaBarge, M. S.; Keul, H.; Kuczkowski, R. L.; Wallasch, M.; Cremer, D. *Ibid.* **1988**, *110*, 2081. (h) Gillies, J. Z.; Gillies, C. W.; Suenram, R. D.; Lovas, F. J.; Stahl, W. *Ibid.* **1989**, *111*, 3073. (i) Bunnelle, W. H.; Meyer, L. A.; Schlemper, E. O. *Ibid.* **1989**, *111*, 7612. (j) Bunnelle, W. H. *Ibid.* **1989**, *111*, 7613. (k) Sugimoto, T.; Nojima, M.; Kusabayashi, S.; McCullough, K. J. *Ibid.* **1990**, *112*, 3690. (l) Jaworski, K.; Smith, L. L. *J. Org. Chem.* **1988**, *53*, 545. (m) Wojciechowski, B. J.; Pearson, W. H.; Kuczkowski, R. L. *Ibid.* **1989**, *54*, 115. (n) Crandall, J. K.; Schuster, T. *Ibid.* **1990**, *55*, 1973.

(3) (a) Miura, M.; Ikegami, A.; Nojima, M.; Kusabayashi, S.; McCullough, K. J.; Nagase, S. *J. Am. Chem. Soc.* **1983**, *105*, 2414. (b) McCullough, K. J.; Nojima, M.; Miura, M.; Fujisaka, T.; Kusabayashi, S. *J. Chem. Soc., Chem. Commun.* **1984**, 35. (c) Miura, M.; Nojima, M.; Kusabayashi, S.; McCullough, K. J. *J. Am. Chem. Soc.* **1984**, *106*, 2932. (d) Miura, M.; Fujisaka, T.; Nojima, M.; Kusabayashi, S.; McCullough, K. J. *J. Org. Chem.* **1985**, *50*, 1504.

(4) Nakamura, N.; Fujisaka, T.; Nojima, M.; Kusabayashi, S.; McCullough, K. J. *J. Am. Chem. Soc.* **1989**, *111*, 1799.

0002-7863/91/1513-1786$02.50/0 © 1991 American Chemical Society