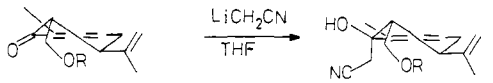
menthone is assigned as the equatorial isomer **17** and that from pulegone as the axial isomer **18**. The change in stereochemistry of attack on menthone presumably derives from the combinatorial effects of the 2-isopropyl substituent and the β-axial hydrogens making the nonbonded interactions dominate over the intrinsic bias for axial attack.

We attribute the ability of the acetonitrile salts to reflect the intrinsic bias of six-membered ring ketones to suffer axial attack to the small steric bulk associated with the attacking end of these ketenimine-type structures. Indeed, the decreasing order of axial selectivity in going from Li^+ to Mg^{2+} agrees with the recent calculations suggesting greater bonding of Mg^{2+} to the carbon, thereby increasing its effective steric bulk. Furthermore, the results also seem to be more in accord with torsional effects rather then orbital distortion as the major contributor to the intrinsic axial bias in nucleophilic addition to six-membered ring ketones. In contrast to the results of Yamamoto, use of the bulky aluminum reagent *decreased* the axial selectivity. The difference may reside in the fact that our nucleophile is a stabilized anion, whereas his were not. The versatility of the nitrile for further structural elaboration makes this method for formation of an axial C–C bond quite synthetically useful. For example, DIBAL-H reduction converts the acetonitrile side chain to an axial acetaldehyde side chain which cannot derive from a crossed aldol condensation. While, at first glance, the case of menthone seems to be a limitation, synthetically, the axial isomer is available by the expedient of employing the unsaturated analogue followed by hydrogenation of its adduct **18** to give the axial isomer **16**. The effect of an α-substituent to disfavor axial attack needs not dominate. In the case of the substrate **20** which bears an α-substituent that hinders axial attack, axial attack still dominated. It appears that by designing an appropriate nucleophile, axial rather than equatorial attack may be more generally available.



20 21

Acknowledgment. We thank the General Medical Sciences Institute of the National Institutes of Health for their generous support of our program. Josepha Florez is a Spanish Ministry of Education and Science Postdoctoral Fellow.

(6) Acetylide additions appear to be axial selective. (a) Hennion, G. F.; O'Shea, F. X. *J. Am. Chem. Soc.* **1958**, *80*, 614. (b) Akhrem, A. A.; Kamernitskii, A. V.; Prohoda, A. M. *Zh. Org. Khim.* **1967**, *3*, 50. (c) Rocquet, F.; Battioni, J. P.; Capmau, M.-L.; Chodkiewicz, W. *C. R. Hebd. Seances Acad. Sci., Ser. C* **1969**, *268*, 1449. (d) Stork, G.; Stryker, J. M. *Tetrahedron Lett.* **1983**, *24*, 4887. (e) Kuwajima, I.; Nakamura, E.; Hashimoto, K. *Tetrahedron* **1983**, *39*, 975. (f) Fleming, I.; Terrett, N. K. *J. Organomet. Chem.* **1984**, *264*, 99.

(7) A 2:1 ratio for addition of lithiated acetonitrile to 4-*tert*-butylcyclohexanone in pentane–ether or PhH–HMPA has been reported. Bellassoued, M.; Dardoize, F.; Gaudemar-Bardone, F.; Gaudemar, M.; Goasdoue, N. *Tetrahedron* **1979**, *32*, 2713. Idriss, N.; Perry, M.; Maroni-Barnaud, Y.; Roux-Schmitt, M.-C.; Seyden-Penne, J. *J. Chem. Res. Synop.* **1978**, 128.

(8) The much higher axial selectivity we observe than previously found may be due to the difference in solvent. Also we find that there is a deterioration of axial selectivity with increased reaction times (normally reactions are complete within 15–30 min) which apparently arises by the addition being somewhat reversible. Such a factor may also be responsible for the lower selectivity of the above report.

(9) All new compounds have been fully characterized and elemental composition established by combustion analysis and/or mass spectroscopy.

(10) Kaneti, J.; Schleyer, P. v. R.; Clark, T.; Kos, A. J.; Spitznagel, G. W.; Andrade, J. G.; Moffat, J. B. *J. Am. Chem. Soc.* **1986**, *108*, 1481. Also see: Kruger, C. *J. Organomet. Chem.* **1967**, *9*, 125. Boche, G.; Marech, M.; Harms, K. *Angew. Chem., Int. Ed. Engl.* **1986**, *25*, 373.

(11) Das, R.; Wilkie, C. A. *J. Am. Chem. Soc.* **1972**, *94*, 4555. Bauer, W.; Seebach, D. *Helv. Chim. Acta* **1984**, *67*, 1972. A correction of the state of aggregation of $LiCH_2CN$ in THF to 2 has been reported as a private communication (see ref 11 in the Kaneti, J., et al. paper, ref 10).

(12) Stothers, J. B. *Carbon-13 NMR Spectroscopy*; Academic Press: New York, 1972. Senda, Y.; Ishiyama, J.; Imaizumi, S. *Tetrahedron* **1975**, *31*, 1601.

(13) Assignment of the ^{13}C signals was facilitated by preparing the adducts with KCD_2CN.

(14) Pansard, J.; Gaudemar, M. *Bull. Soc. Chim. Fr.* **1973**, *12*, 3472.

[6 + 3] Cycloaddition to Nine-Membered Ring Carbocycles

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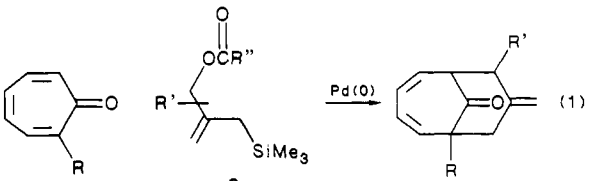
Received July 29, 1986

The Diels–Alder reaction continues to prove itself as the most important six-membered ring-forming reaction. In searching for alternative cycloaddition strategies for ring construction, we hoped that any such methods developed would be applicable to a variety of ring sizes. FMO theory suggests that tropones should preferentially react at C(2) and C(7) rather than C(2) and C(3).[1,2] Indeed, in cycloadditions of dienes with these acceptors, a [6 + 4] pathway may compete with and/or dominate the [4 + 2] reaction.[3] We wish to record our preliminary observations that demonstrate that 2-[(trimethylsilyl)methyl]allyl carboxylates[4] and their substituted analogues[5] not only can form five-membered rings[6] but undergo exclusive [6 + 3] nine-membered carbocycle formation in their reactions with tropones according to eq 1. To our knowledge, this reaction is the first report of a [6 + 3] cycloaddition.



1 2 3

In order to test the feasibility of [6 + 3] cycloaddition of **2**, R′ = H and R″ = CH_3, with tropone, we reacted a 1:1 mixture of the two in toluene at 80 °C using 2.5 mol % of a Pd(0) catalyst generated in situ by mixing palladium acetate and triisopropyl phosphite, the latter serving as both reductant and ligand.[5] A 68% yield of a single crystalline (mp 85–86 °C) adduct is formed whose spectral properties identify it as the desired [6 + 3] adduct **3**, R = R′ = H.[7] The symmetry of the adduct is clearly visible by the simplicity of the ^1H NMR spectrum [δ 5.80 (td, J = 12.0, 3.1 Hz, 2 H), 5.42 (m, 2 H), 4.95 (appt., J = 1.5 Hz, 2 H), 3.37 (appt., J = 6.0 Hz, 2 H), 2.72 (ddd, J = 13.0, 6.0, 1.5 Hz, 2 H), 2.43 (d, J = 13.0 Hz, 2 H)].

The examples summarized in Table I attest to the generality of this reaction. To examine the role of the electrophilicity of the tropone, we placed electron-donating groups at the 2-position

(1) Salem, L. *J. Am. Chem. Soc.* **1968**, *90*, 543. Biggi, G.; Deloma, F.; Pietra, F. *J. Am. Chem. Soc.* **1973**, *95*, 7101. For a review, see: Pietra, F. *Acc. Chem. Res.* **1979**, *12*, 132.

(2) For anion additions to tropone and its use in natural products syntheses, see: Rigby, J.; Wilson, J. Z. *J. Am. Chem. Soc.* **1984**, *106*, 8217.

(3) Ito, S.; Fujise, Y.; Okuda, T.; Inone, Y. *Bull. Chem. Soc. Jpn.* **1966**, *39*, 1351. Cookson, R. C.; Drake, B. V.; Hudec, J.; Morrison, A. *Chem. Commun.* **1966**, 15. Ito, S.; Otani, H.; Narita, S.; Honma, H. *Tetrahedron Lett.* **1972**, 2223. Mukai, T.; Akasaki, Y.; Hagiwara, T. *J. Am. Chem. Soc.* **1972**, *94*, 675. Garst, M. E.; Roberts, V. A.; Prussin, C. *Tetrahedron* **1978**, *39*, 581. Fujise, Y.; Shiokawa, T.; Mazaki, Y.; Fukazawa, Y.; Fujii, M.; Ito, S. *Tetrahedron Lett.* **1982**, *23*, 1601. Mukerjee, D.; Watts, C. R.; Houk, K. N. *J. Org. Chem.* **1983**, *43*, 817. Garst, M. E.; Roberts, V. A.; Houk, K. N.; Rondan, N. G. *J. Am. Chem. Soc.* **1984**, *106*, 3882. Paquette, L. A.; Hathaway, S. J.; Schirch, P. F. T. *J. Org. Chem.* **1985**, *50*, 4199. Rigby, J. H.; Moore, T. L.; Rege, S. *J. Org. Chem.* **1986**, *51*, 298. Funk, R. L.; Bolton, G. L. *J. Am. Chem. Soc.* **1986**, *108*, 4655.

(4) Trost, B. M.; Chan, D. M. T. *J. Am. Chem. Soc.* **1983**, *105*, 2315, 2326.

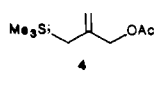
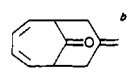
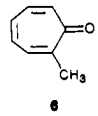
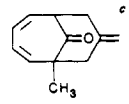
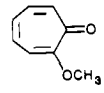
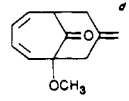
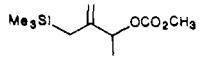
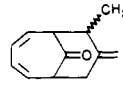
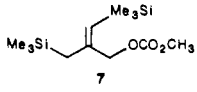
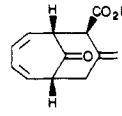
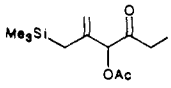
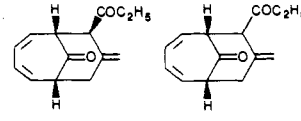
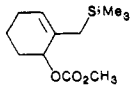
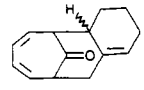
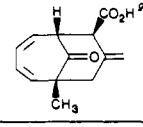
(5) Trost, B. M.; Nanninga, T. N.; Satoh, T. *J. Am. Chem. Soc.* **1985**, *107*, 721.

(6) Trost, B. M. *Angew. Chem., Int. Ed. Engl.* **1986**, *25*, 1. For a review of a related reaction of methylenecyclopropanes, see: Binger, P.; Buch, H. M. *Topics Curr. Chem.* **1986**, 135, 000.

(7) All new compounds have been fully characterized and have had elemental compositions determined by combustion analysis and/or high-resolution mass spectroscopy.

0002-7863/87/1509-0615$01.50/0

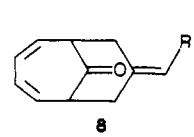
Table I. [6 + 3] Cycloadditions[a]

entry	TMM precursor	tropone	reaction time, h	prod[h]	isolated yield, %
1	 **4**	 **5**	3	 [b]	68
2	**4**	 **6**	10	 [c]	74
3	**4**		6	 [d]	41
4		**5**	6	 1:1	46
5	 **7**	**5**	6	 [e]	84
6		**5**	3	 3:1[f]	81
7		**5**	3	 3:2	81
8	**7**	**6**	12	 [g]	62

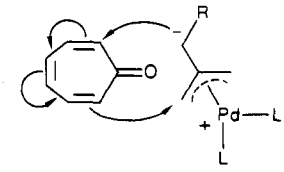
[a] All reactions were run on 1–5-mmol scale using a ratio of TMM precursor–tropone of 1:1–1.5:1 at 0.67 M in $PhCH_3$. The catalyst was prepared by mixing 2.5 mol % palladium acetate with 22 mol % triisopropyl phosphite. The reaction was immersed into an oil bath preheated to 80–85 °C for the stated time. Evaporation of solvent followed by flash chromatography gave the adducts. [b] Mp 85–86 °C. [c] Mp 64–65 °C. [d] Mp 58–60 °C. [e] Mp > 230 °C. [f] Mp 94.5–96 °C. [g] Mp 130–135 °C. [h] Reference 7.

(entries 2[8] and 3[9]). Both served as suitable acceptors, although a somewhat lower yield was obtained with tropolone methyl ether.

Having established the ability to place substituents on the tropone nucleus, we turned to the effect of substituents on the trimethylenemethane (TMM) precursors. As entries 4–7 demonstrate, both electron-donating and electron-withdrawing substituents are compatible and produce the [6 + 3] cycloadducts, with high regioselectivity. Use of carbonate rather than acetate as the leaving group is required for the alkyl-substituted TMM systems. Unlike most organic reactions, the regioselectivity is independent of the electronic nature of the substituent. No product bearing the substituent at the olefinic carbon as in **8** was observed in any case. Theory predicts that the unsymmetrical complex depicted in **9** is the thermodynamically most stable regardless of the nature of the substituent.[10] Thus, the regioselectivity can be understood as arising via a cycloaddition, either concerted or stepwise, as depicted in **9**.

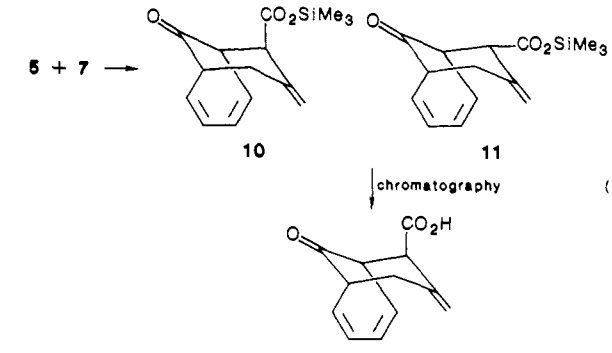


8



9

The stereochemistry of the products depends upon the nature of the substituents—alkyl substitutents give mixtures (entries 4 and 7) but electron-withdrawing groups give high diastereoselectivity (entries 5 and 6). Examination of the crude reaction mixture from the reaction of entry 5, which involves an in situ carboxylation prior to cycloaddition,[11] reveals that the initial product is indeed a mixture of the trimethylsilyl esters **10** and **11**.



10 **11** **12**

(2)

(8) 2-Methyltropone was prepared according to: Doering, W. von E.; Hiskey, C. F. *J. Am. Chem. Soc.* **1952**, *74*, 5688.

(9) Tropolone methyl ether was prepared according to: Minns, R. *Org. Synth.* **1977**, *57*, 117. Evans, D. H.; Greenwald, R. B. *Org. Prep. Proced.* **1972**, *4*, 75.

(10) Gordon, D. J.; Fenske, R. F.; Nanninga, T. N.; Trost, B. M. *J. Am. Chem. Soc.* **1981**, *103*, 5974.

However, chromatography delivers a single product **12** which arises by equilibration to the thermodynamically most stable one and desilylation of the silyl ester. NMR spectroscopy establishes the axial nature of the carboxylic acid group. MM-2 calculations support the notion that J_{ab} for **12** should be around 0–2 Hz, whereas the same coupling for the compound epimeric at the carboxyl-bearing carbon should be 4–7 Hz. These predictions correspond well to the observed couplings of the parent adduct (<1 and 6.0 Hz, respectively). The appearance of H_a at δ 3.69 as a broad singlet ($J < 1$ Hz) supports the assignment as the exo carboxylic acid; consideration of A-strain effects also predicts the axial carboxylic acid to be more stable. MM-2 calculations support the higher stability for the axial isomer too.

To determine the initial bonding site in the tropone partner, a double-labeling experiment is necessary. In this case, the 2-methyltropone was reacted with **7**, which undergoes in situ carboxylation prior to cycloaddition (entry 8). As for the case of entry 5, a stereoisomeric mixture initially forms which equilibrates to the exo carboxylic acid product depicted. The presence of an isolated AB pattern for the allylic methylene group (δ 2.65 and 2.42, J = 13.5 Hz) and a broad singlet for the allylic methine proton (δ 3.69) establishes both the regio- and stereochemistry.

In contrast to the reaction of dienes with tropone where several modes of reaction have been observed,[3] the reaction of the bifunctional conjunctive reagent **4** and its analogues with tropone proceeds only via the [6 + 3] mode. Furthermore, the reaction is highly chemo- and regioselective and, in the case of electron-withdrawing groups, highly diastereoselective. The versatility of the bridging ketone and the ease with which such a one-carbon bridge may be cleaved make these adducts flexible nine-membered ring intermediates. The ability of the cyclic TMM precursor of entry 7 to participate demonstrates the rapidity with which polycyclic systems may be constructed. it appears that these TMM synthons can permit an approach to a number of odd-membered rings via [2n + 3] cycloadditions. So far, syntheses of five- (n = 1) and nine-membered (n = 3) rings have been proven to be feasible. In both cases, the question of concerted vs. stepwise reactions must be considered open. The developing parallel between the reactions of these bifunctional conjunctive reagents and those of dienes, especially electron-rich dienes such as Danishefsky's diene,[12] begins to suggest that similar mechanisms may be involved.

Acknowledgment. We thank the National Science Foundation for their generous support of our programs.

(11) Trost, B. M.; Migani, S. *J. Am. Chem. Soc.* **1986**, *108*, 6051.
(12) Danishefsky, S. *Acc. Chem. Res.* **1981**, *14*, 400.

Kinetics of ^{13}CO Exchange with ^{12}CO in $[HM_3(^{12}CO)_{11}]^-$ and $[DM_3(^{12}CO)_{11}]^-$ (M = Ru or Os): Relationship between Exchange Pathway and Catalytic Activity in the Catalysis of the Water Gas Shift Reaction

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The anion $[HRu_3(CO)_{11}]^-$ has been implicated as an active participant in the catalysis of the water gas shift reaction.[1,2] On the other hand, $[HOs_3(CO)_{11}]^-$ is less active under similar conditions.[3] The kinetics of ^{13}CO exchange with ^{12}CO in $[HM_3(^{12}CO)_{11}]^-$ and $[DM_3(^{12}CO)_{11}]^-$ (M = Ru, Os) in THF[4] provide further insight into the nature of the catalysis of the water gas shift reaction by $[HRu_3(CO)_{11}]^-$ and reveal a basis for the apparent difference in activity between $[HRu_3(CO)_{11}]^-$ and $[HOs_3(CO)_{11}]^-$.

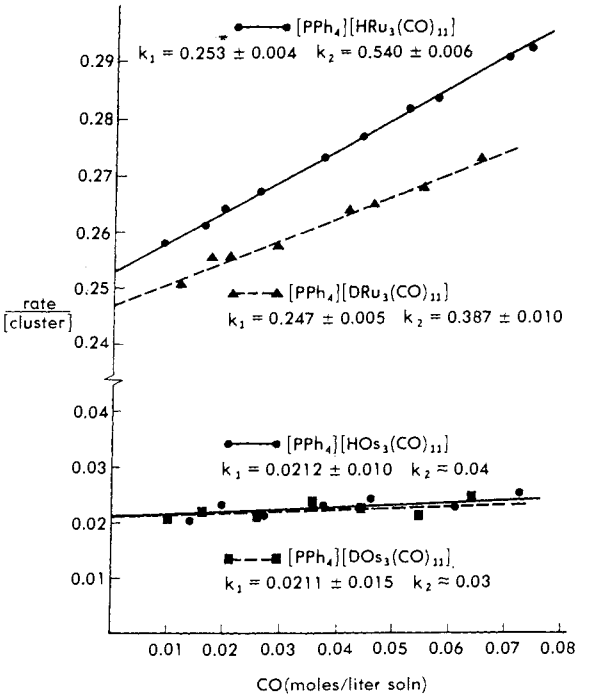

Figure 1. Plot of rate/[cluster] vs. CO concentration in solution.

Exchange between ^{13}CO and ^{12}CO in $[HRu_3(^{12}CO)_{11}]^-$ in THF[4] (20–30 °C, 0.001–0.01 M $[HRu_3(CO)_{11}]^-$, 0.0007–0.033 M CO) appears to occur through parallel first- and second-order reactions. The overall rate expression for the forward exchange reaction is given by eq A, where concentrations are given in moles per liter

$$\text{rate} = k_1[\text{cluster}] + k_2[\text{cluster}][\text{CO}] \qquad \text{(A)}$$

of solution. A plot of rate/[cluster] vs. [CO] is linear (Figure 1). For $[PPh_4][HRu_3(CO)_{11}]$ at 298 K, $k_1 = 0.253 \pm 0.004$ s^{-1} and $k_2 = 0.540 \pm 0.006$ M^{-1} s^{-1}. For k_1, $\Delta H_1^{\ddagger} = 19.8 \pm 0.6$ kcal/mol and $\Delta S_1^{\ddagger} = 5.3 \pm 1.5$ cal/mol K; for k_2, $\Delta H_2^{\ddagger} = 14.1 \pm 0.5$ kcal/mol and $\Delta S_2^{\ddagger} = -8.0 \pm 1.7$ cal/mol K. Entropies of activation, $\Delta S_1^{\ddagger}$ and $\Delta S_2^{\ddagger}$, are consistent with dissociative and associative processes, respectively. Thus, at low ^{13}CO concentration an apparent dissociative step forming $[HRu_3(CO)_{10}]^-$ plus CO appears to dominate the exchange process. The dissociative pathway confirms a suggestion by Darensbourg,[8a] and k_1 is

(1) (a) Bricker, J. C.; Nagel, C. C.; Bhattacharyya, A. A.; Shore, S. G. *J. Am. Chem. Soc.* **1985**, *107*, 377. (b) Bricker, J. C.; Nagel, C. C.; Shore, S. G. *J. Am. Chem. Soc.* **1982**, *104*, 1444.
(2) Ungermann, C.; Landis, V.; Moya, S. A.; Cohen, H.; Walker, H.; Pearson, R. G.; Rinker, R. G.; Ford, P. C. *J. Am. Chem. Soc.* **1979**, *101*, 5922.
(3) (a) Ford, P. C.; Ungermann, C.; Landis, V.; Moya, S. A.; Rinker, R. C.; Laine, R. M. *Adv. Chem. Ser.* **1979**, *173*, 81. (b) Pettit, R.; Cann, K.; Cole, T.; Mauldin, C. H.; Slegeir, W. *Adv. Chem. Ser.* **1979**, *173*, 121.
(4) (a) Kinetic measurements were made by using a thermostated gas infrared cell with a cold finger to hold the continuously stirred reaction solution. Reaction conditions: 0.1–2.5 atm of ^{13}CO; 20.0 ± 0.2 to 35.0 ± 0.2 °C; anion concentration = 0.001–0.01 M. With the $[PPh_4]^+$ counterion and under these conditions, $Ru_3(CO)_{12}$ does not appear to form.[1] The forward reaction was followed by monitoring the 2171-cm^{-1} band of free ^{12}CO as it appeared in the gas phase over the stirred solution. A Mattson Instruments Cygnus 25 FTIR spectrometer was programmed to collect spectra at desired intervals and acquisition times. Time vs. absorbance data were analyzed by using a standard rate-fitting computer program and the McKay equation for isotopic exchange.[5] The solubility of CO in THF was determined over the temperature and pressure range employed in this study by using a modification of a known procedure.[6] At 1 atm of CO pressure, its solubility in THF is 0.0109 ± 0.0005 M (25 °C) and 0.0117 ± 0.0003 M (30 °C). Its solubility in THF increases with increasing temperature, consistent with results from other ether solvents.[7]
(5) (a) McKay, H. A. C. *J. Am. Chem. Soc.* **1943**, *65*, 702. (b) Espenson, J. H. *Chemical Kinetics and Reaction Mechanisms*; McGraw Hill: NY, **1981**; p 51.
(6) Rivas, O. R.; Prausnitz, J. M. *Ind. Eng. Chem. Fundam.* **1979**, *18*, 289.
(7) Calderazzo, F.; Cotton, F. A. *Inorg. Chem.* **1962**, *1*, 30.

0002-7863/87/1509-0617$01.50/0