Sakurai Reaction Addition of 1,8-Bis(trimethylsilyl)-2,6-octadiene to α,β-Enones. A One-Step Control of Four Stereogenic Carbon Centers

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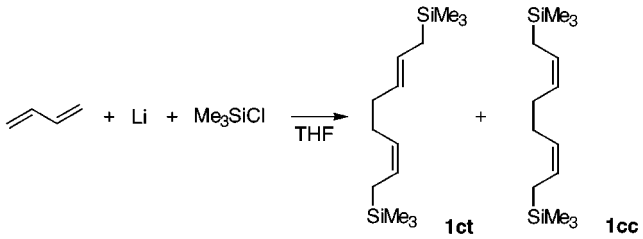
Received September 9, 1997

The addition reaction of 1,8-bis(trimethylsilyl)-2,6-octadiene with open-chain conjugated enones in the presence of titanium tetrachloride affords 4,7-divinyldecane-1,10-diones with very high diastereoselectivity. In the case of benzalacetone (*trans*-4-phenyl-3-buten-2-one), the structure of the adduct (74% yield) was established as the meso isomer (4*S**,5*R**,8*S**,9*R**)-4,9-diphenyl-5,8-divinyldodecane-2,11-dione by a single-crystal X-ray analysis.

Important progress in organic synthesis has come from the stereoselectivity of the C−C bond-forming reactions.[3] The Lewis acid mediated reaction constitutes an indispensable part of modern synthetic chemistry, especially in the art of acyclic stereocontrol.[4] Among a number of reactive reagents, allylsilanes are important for achieving C−C bond formation by addition to aldehydes or enones.[5]

Recently, we have developed the chemistry of the 1,8-bis(trimethylsilyl)-2,6-octadiene (BISTRO, **1**), easily obtained in one step from 1,3-butadiene.[6] The present paper is concerned with the $TiCl_4$-mediated addition of **1** with α,β-enones.[7]

BISTRO, synthesized by Li reduction of 1,3-butadiene in the presence of chlorotrimethylsilane, is an inseparable mixture of (*Z*,*Z*) (ca. 50%) **1cc**, (*Z*,*E*) (ca. 40%) **1ct**, and



(*E*,*E*) (4%) isomers contaminated with ca. 4% of (2*Z*)-1,6-bis(trimethylsilyl)-2,7-octadiene and ca. 2% of (2*E*)-1,6-bis(trimethylsilyl)-2,7-octadiene.[6f] In contrast, if the reduction is carried out with Na, the major (90%) isomer is **1cc**.

Focusing on the Sakurai reaction of **1** with benzalacetone (*trans*-4-phenyl-3-buten-2-one, **2a**), we investigated this reaction in order to evaluate the diastereoselectivity (Scheme 1). Initially, **1** (stereoisomer mixture) (2.5 equiv) was allowed to react with **2a** in CH_2Cl_2 solution in the presence of $TiCl_4$ (1.3 equiv). Diketone **3a** (25%) and ketone **6** (as a mixture of isomers) (41%) were isolated along with recovered **2a** (19%). A considerable improvement was achieved by the addition of nitromethane (4 equiv) to the reaction, and diketone **3a** could be obtained as major product (74%) along with ketones **4a** (14%) and **5** (6%).

The cyclopentyl derivative **6** presumably arises from an intramolecular cyclization involving the β-silyl cation **7**. The presence of nitromethane does not allow for the formation of the unwanted ketone **6** by increasing the rate of β-desilylation from cation **7**.[8]

In the expected mechanism, the first step of the Sakurai reaction is the formation of a β-silyl cation.[4b] Then, the addition of a chloride anion to silicon atom allows the restoration of the allylic system with rear-

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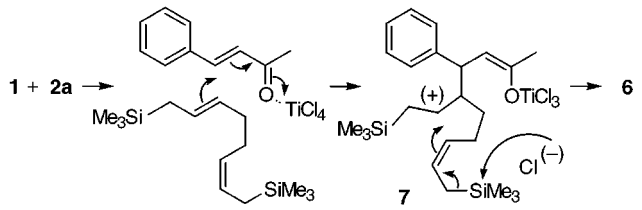
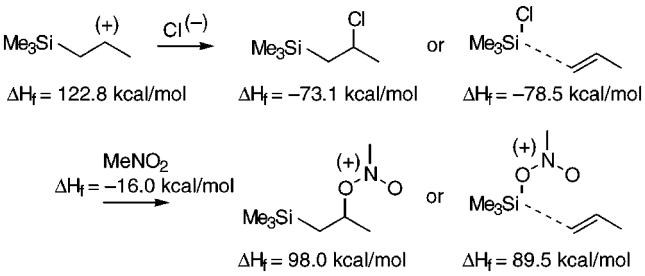
(8) The use of nitrobenzene led to similar results. The nitro group can be present on the chain of the electrophilic reagent with the same efficiency. The influence of the nitro group during the reaction of **1** to various electrophilic compounds was previously discussed, see: Tubul, A.; Ouvrard, P.; Santelli, M. *Bull. Soc. Chim. Fr.* **1992**, *129*, 265−269. Increasing of stereoselectivity was also observed by addition of hexamethylphosphorotriamide or triphenylphosphine, see: (a) Pan, L.-R.; Tokoroyama, T. *Chem. Lett.* **1990**, 1999−2002. (b) Kadota, I.; Gevorgyan, V.; Yamada, J.-i; Yamamoto, Y. *Synlett* **1991**, 823−824. (c) Suzuki, I.; Yamamoto, Y. *J. Org. Chem.* **1993**, *58*, 4783−4784.

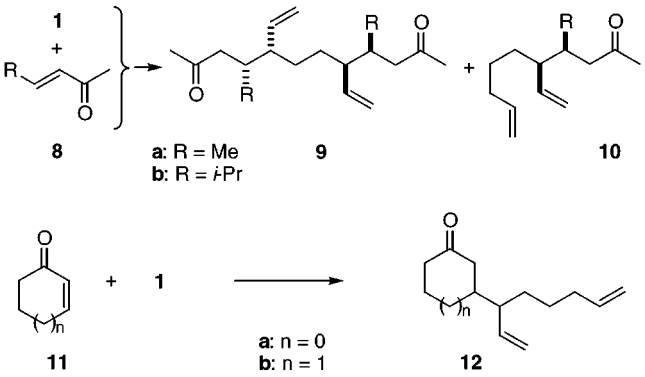
S0022-3263(97)01677-0 CCC: $15.00
Published on Web 03/11/1998



rangement. Calculations by the PM3 method[9] confirm that the addition of the chloride anion on silicon atom is preferable to the attack on the carbocation ($\delta\Delta H_f = -5.4$ kcal/mol). Its structure corresponds to propene associated with chlorotrimethylsilane. In the same way, we have calculated the complexes resulting from the addition of nitromethane to carbocation or silicon atom. Similarly, the most stable complex ($\delta\Delta H_f = -8.5$ kcal/mol) arises from the addition of nitromethane to silicon atom. It involves an association between propene and *O*-(trimethylsilyl)nitromethane cation.



The preparation of stereochemically pure **3a** (up to 95%, according to ^{1}H NMR analysis) constitutes *a one-step controlled formation of four stereogenic carbon centers on an acyclic product*.[10] The stereochemistry of **3a** was determined by X-ray analysis[11] and showed as the meso isomer (4*S**,5*R**,8*S**,9*R**)-4,9-diphenyl-5,8-divinyldodecane-2,11-dione. The reaction could be generalized to various enones. Effectively, enones **2** and **8** reacted with similar diastereoselectivities (see Table 1). In contrast, addition of **1** to cyclopentenone **11a** or cyclohexenone **11b** occurred with a low yield (18%, 56%, respectively) to give the product of monoalkylation (**12**).



(9) Stewart, J. J. P. *J. Comput. Chem.* **1989**, *10*, 209−220 and 221−264.

(10) The addition reaction of BISTRO with aldehydes occurs stereoselectively, see ref 6f.

(11) The authors have deposited atomic coordinates for this structure with the Cambridge Crystallographic Data Centre. The coordinates can be obtained, on request, from the Director, Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge, CB2 1EZ, U.K.

Scheme 1

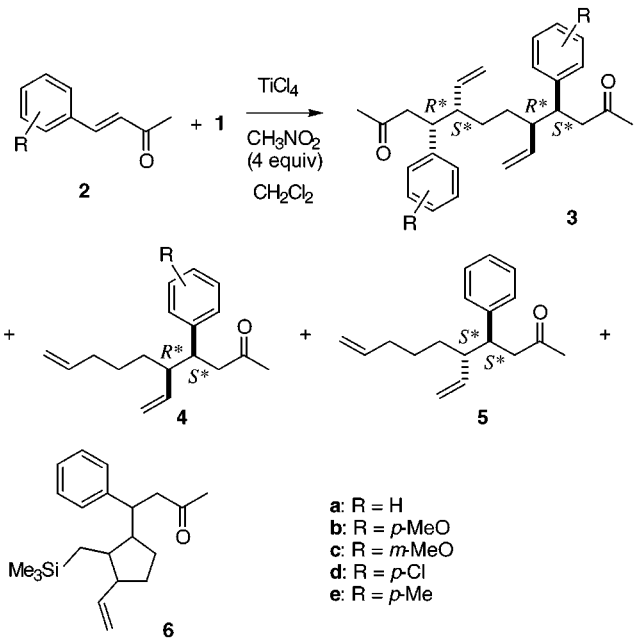


Table 1. Sakurai Reaction Addition of 1 to Ketones 2b−e and 8a,b

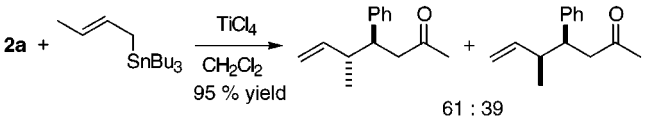
entry	enones	products (yield, %)
1	**2b**	**3b** (62), **4b** (30)
2	**2c**	**3c** (68), **4c** (22)
3	**2d**	**3d** (72), **4d** (23)
4	**2e**	**3e** (70), **4e** (22)
5	**8a**	**9a** (61), **10a** (17)
6	**8b**	**9b** (74), **10b** (26)

It is known that the diastereoselectivity of the reaction of allylsilanes (particularly (*Z*)- and (*E*)-crotylsilanes) or allylstannanes with enones, acyl cyanides, or diethyl ethylidenemalonates depends on the geometry of the double bond.[12,13] For instance,the addition of (*E*)-crotyltin to benzalacetone (**2a**) proceeds quite smoothly with a moderate anti selectivity.[12o]

The obtention of only one diastereomer (**3**) constitutes a puzzling fact since **1** is a mixture of isomers. With the

(12) (a) Hosomi, A.; Sakurai, H. *J. Am. Chem. Soc.* **1977**, *99*, 1673−1675. (b) Ojima, I.; Kumagai, M.; Miyazawa, Y. *Tetrahedron Lett.* **1977**, 1385−1388. (c) Hosomi, A.; Hashimoto, H.; Kobayashi, H.; Sakurai, H. *Chem. Lett.* **1979**, 245−248. (d) Hosomi, A.; Kobayashi, H.; Sakurai, H. *Tetrahedron Lett.* **1980**, *21*, 955−958. (e) Jellal, A.; Santelli, M. *Tetrahedron Lett.* **1980**, *21*, 4487−4490. (f) Yanami, T.; Miyashita, M.; Yoshikoshi, A. *J. Org. Chem.* **1980**, *45*, 607−612. (g) Heathcock, C. H.; Kleinman, E. F.; Binkley, E. S. *J. Am. Chem. Soc.* **1982**, *104*, 1054−1068. (h) Heathcock, C. H.; Kiyooka, S.; Blumenkopf, T. A. *J. Org. Chem.* **1984**, *49*, 4214−4223. (i) Santelli, M.; El Abed, D.; Jellal, A. *J. Org. Chem.* **1986**, *51*, 1199−1206. (j) Yamamoto, Y.; Nishii, S.; Maruyama, K. *J. Chem. Soc., Chem. Commun.* **1985**, 386. (k) Heathcock, C. H.; Smith, K. M.; Blumenkopf, T. A. *J. Am. Chem. Soc.* **1986**, *108*, 5022−5024. (l) Yamamoto, Y. *Acc. Chem. Res.* **1987**, *20*, 243−249. (m) Yamamoto, Y.; Nishii, S.; Ibuka, T. *J. Chem. Soc., Chem. Commun.* **1987**, 464. (n) Mobilio, D.; De Lange, B. *Tetrahedron Lett.* **1987**, *28*, 1483−1486. (o) Yamamoto, Y.; Nishii, S. *J. Org. Chem.* **1988**, *53*, 3597−3603. (p) Yamamoto, Y.; Sasaki,.N. *Stereochem. Organomet. Inorg. Compd.* **1989**, *3*, 363−441. (q) Tokoroyama, T.; Pan, L.-R. *Tetrahedron Lett.* **1989**, *30*, 197−200. (r) Knölker, H.-J.; Jones, P. G.; Pannek, J.-B. *Synlett* **1990**, 429−430. (s) See ref 8a. (t) Jeroncic, L. O.; Cabal, M.-P.; Danishefsky, S. J.; Shulte, G. M. *J. Org. Chem.* **1991**, *56*, 387−395. (u) Pan, L.-R.; Tokoroyama, T. *Tetrahedron Lett.* **1992**, *33*, 1469−1472. (v) Schultz, A. G.; Lee, H. *Tetrahedron Lett.* **1992**, *33*, 4397−4400. (w) Panek, J. S.; Jain, N. F. *J. Org. Chem.* **1993**, *58*, 2345−2348. (x) Sato, M.; Aoyagi, S.; Yago, S.; Kibayashi, C. *Tetrahedron Lett.* **1996**, *37*, 9063−9066. (y) Tori, M.; Ikawa, M.; Sagawa, T.; Furuta, H.; Sono, M.; Asakawa, Y. *Tetrahedron* **1996**, *52*, 9999−10010.

(13) The Sakurai reaction of (*E*)- and (*Z*)-crotylsilanes with cyclohexenone or cyclopentenone showed respectively high syn and low anti selectivities, see refs 12q,s,t.



aim of determining the relative reactivity of **1cc** and **1ct**, we carried out the reaction with an excess of **1** (2.5 equiv), and we observed that the recovered BISTRO was only the (*Z*,*Z*)-isomer **1cc**. Thus, the minor isomer **1ct** seems to be the most reactive.[14] Afterward, **1cc** (obtained as a single product from reductive dimerization of 1,3-butadiene using sodium instead of lithium) was involved in the addition reaction with **2a**. The same meso isomer **3a** was isolated in a lower yield (30%) along with **4a** (21%) generated with an amazing high diastereoselectivity (up to 80%).

It is clear that the conformational preferences of the Lewis acid carbonyl complex are ultimately responsible for determining the stereochemical course of Lewis acid mediated reactions. Titanium(IV) Lewis acids have a strong preference for a six-coordinated, octahedral arrangement. Thus, the acid:carbonyl stoichiometry for these complexes is often 1:2.[15] These complexes promise to be useful in synthesis because the carbonyl substrate is more susceptible to nucleophilic attack. The stereochemistry of addition should be easier to control, since adducts of bidentate Lewis acids will have a more restricted range of conformations.[16] To attempt a rationalization of the stereochemical outcome of the reaction, some information about the conformation of the benzalacetone−$TiCl_4$ complex were required. Therefore, ^1H and ^{13}C NMR studies were undertaken in order to investigate the complexation[17] between ketone and $TiCl_4$ and the structure of the subsequent enolate resulting from the Sakurai addition.[18]

In a NMR tube, a 0.3 M solution of benzalacetone in CD_2Cl_2 was cooled at −60 °C and 0.25, 0.5, 0.75, and then 1.0 molar equiv of $TiCl_4$ was successively added. Upon addition of $TiCl_4$, a shift of relevant signals was observed. Upon addition of 0.25 equiv of Lewis acid, both the signals of the free ketone and the transient 1:1 complex of benzalacetone and $TiCl_4$ were observed (relative intensity 3:1). This 1:1 complex is converted into a 2:1 complex (relative intensity 1:1) in 1 h (**2a**, Me; $\delta = 2.36$ ppm; **2a** + 0.25 $TiCl_4$, Me, $\delta = 2.49$ (br) and 2.85 ppm (rel int 3:1). Moreover, if benzalacetone was added to 0.25 equiv of $TiCl_4$ in CD_2Cl_2, free benzalacetone and a 2:1 complex of benzalacetone and $TiCl_4$ were observed (rel int 1:1) (0.25 $TiCl_4$ + **2a**; Me, $\delta = 2.54$ (br) and 2.85 ppm (rel int 1:1). Thus, the first complex exhibiting a 1:1 structure becomes rapidly a 2:1 complex. When 0.5 equiv of $TiCl_4$ was present, the only observable signals were assigned to the 2:1 complex of benzalacetone and $TiCl_4$. Further addition of $TiCl_4$ (0.75 and 1 equiv) did not change the NMR spectra, but significant line broadening indicative of dynamic behavior was observed with 1 equiv. Another series of experiments was carried out by adding 2 molar equiv of nitromethane after addition of 0.5, 0.75, or 1 molar equiv of $TiCl_4$. No change in the NMR spectra of the 2:1 complex of benzalacetone and $TiCl_4$ could be observed. In contrast, the chemical shift of the methyl group of nitromethane was observed downfield.[19] Finally, to a 0.3 M solution of benzalacetone in CD_2Cl_2 maintained at −50 °C were successively added 1.1 molar equiv of $TiCl_4$, 4 molar equiv of nitromethane, and 2 molar equiv of allyltrimethylsilane.[20] After 18 h, the ^{13}C NMR spectrum was recorded. Signals corresponding to the formation of titanium enolate **13** were detected at C(2) = 168.8 and C(3) = 120.3 ppm. They did not change after warming to room temperature.[21,22] To determine the geometry of **13**, we decided to generate it by reaction of the corresponding enoxysilane **15** with $TiCl_4$. From ketone **14**, a 3.3:1 mixture of **15Z** and **15E** was obtained (signals of vinyl proton H(3) respectively at 4.67 and 4.88 ppm, confirmed by difference NOE spectrum obtained by irradiation of the methyl signal at 1.81 ppm).[23] By addition of $TiCl_4$ to a solution of **15** in $CDCl_3$ maintained at −60 °C, signals at 168.0 and 120.3 ppm were observed.[24] This detailed study shows that benzalacetone was in an s-cis conformation in a 2:1

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(16) Structural data concerning titanium(IV) Lewis acids show a strong preference for a six-coordinate structure with a distorted octohedral arrangement; see refs 4b and 15. Most of the $TiCl_4$−Lewis base adducts with chelating agent were found to have only the cis configuration, the chelate ligand, and titanium atom form a five to seven-membered ring, see: (a) Utko, J.; Sobota, P.; Lis, T. *J. Organomet. Chem.* **1987**, *334*, 341−345. (b) Poll, T.; Metter, J. O.; Helmchen, G. *Angew. Chem., Int. Ed. Engl.* **1985**, *24*, 112−114. But dimeric units of two octahedral titaniums with bridging chlorine atoms are observed when only a single equivalent of the carbonyl base is present, see: (c) Brun, L. *Acta Crystallogr.* **1966**, *20*, 739−749. (d) Bachand, B.; Bélanger-Gariépy, F.; Wuest, J. D. *Organometallics* **1990**, *9*, 2860−2862. (e) Simard, M.; Vaugeois, J.; Wuest, J. D. *J. Am. Chem. Soc.* **1993**, *115*, 370−372. Calculations reveal that the more stable $TiCl_4$−formaldehyde complex was the 2:1 with the two carbonyl group cis coordinated to the titanium atom, see: Branchadell, V.; Oliva, A. *J. Am. Chem. Soc.* **1992**, *114*, 4357−4364.

(17) (a) Childs, R. F.; Mulholland, D. L.; Nixon, A. *Can. J. Chem.* **1982**, *60*, 801−808. (b) Castellino, S. *J. Org. Chem.* **1990**, *55*, 5197−5200.

(18) The rationale for investigating the well-known conjugate reduction reaction as a means of stereoselective enolate formation was based on the supposition that known ground-state conformational preferences of enones might be reflected in the resultant enolate ratios, see: Chamberlin, A. R.; Reich, S. H. *J. Am. Chem. Soc.* **1985**, *107*, 1440−1441.

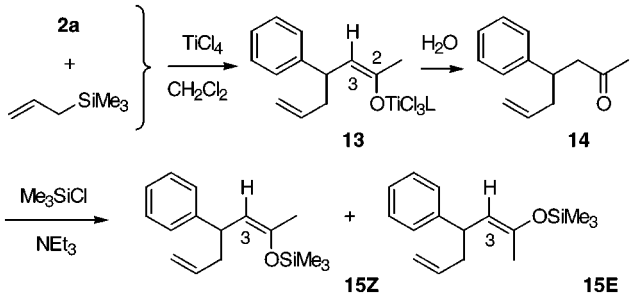
(19) X-ray studies of nitromethane and $TiCl_4$ show formation of a 1:1 dimeric complex with only one oxygen atom of the nitro group bound to titanium, see: Boyer, M.; Jeannin, Y.; Rocchiccioli-Deltcheff, C.; Thouvenot, R. *J. Coord. Chem.* **1978**, *7*, 219−226.

(20) Addition of allylsilane to benzalacetone, see: (a) Hosomi, A.; Shirahata, A.; Sakurai, H. *Tetrahedron Lett.* **1978**, 3043−3046. (b) Sakurai, H.; Hosomi, A.; Hayashi, J. *Org. Synth.* **1984**, *62*, 86−94. (c) Majetich, G.; Casares, A.; Chapman, D.; Behnke, M. *J. Org. Chem.* **1986**, *51*, 1745−1753. Addition of *trans*-crotyltin to benzalacetone proceeds with anti selectivity (anti−syn = 1.63:1), see ref 12o. For addition reactions of stannylallenes to benzalacetone, see: (a) Haruta, J.-i.; Nishi, K.; Matsuda, S.; Tamura, Y.; Kita, Y. *J. Chem. Soc., Chem. Commun.* **1989**, 1065. (b) Haruta, J.-i.; Nishi, K.; Matsuda, S.; Akai, S.; Tamura, Y.; Kita, Y. *J. Org. Chem.* **1990**, *55*, 4853−4859.

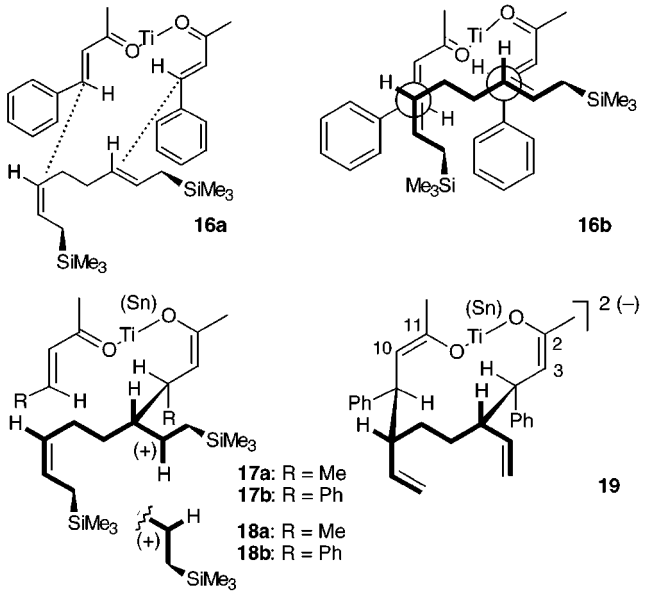
(21) Titanium enolates resulting from the addition of allyltrimethylsilane to cyclohexenones were observed by ^{13}C NMR, see: Denmark, S. E.; Almstead, N. G. *Tetrahedron* **1992**, *48*, 5565−5578. For trapping of one of these titanium enolates, see: Neunert, D.; Klein, H.; Welzel, P. *Tetrahedron* **1989**, *45*, 661−672. For NMR data concerning the geometry of trichlorotitanium enolates, see: (a) Nakamura, E.; Shimada, J.-i.; Horiguchi, Y.; Kuwajima, I. *Tetrahedron Lett.* **1983**, *24*, 3341−3342. (b) Xiang, Y. B.; Olivier, E.; Ouimet, N. *Tetrahedron Lett.* **1992**, *33*, 457−460.

(22) Titanium enolates are prepared by Evans' procedure: (a) Evans, D. A.; Rieger, D. L.; Bilodeau, M. T.; Urpi, F. *J. Am. Chem. Soc.* **1991**, *113*, 1047−1049. (b) Evans, D. A.; Bilodeau, F.; Somers, T. C.; Clardy, J.; Cherry, D.; Kato, Y. *J. Org. Chem.* **1991**, *56*, 5750−5752. (c) Annunziata, R.; Cinquini, M.; Cozzi, F.; Cozzi, P. G. *J. Org. Chem.* **1992**, *57*, 4155−4162. By transmetalation: (d) Duthaler, R. O.; Hafner, A.; Riedeker, M. *Pure Appl. Chem.* **1990**, *62*, 631−642. (e) Nerz-Stormes, M.; Thornton, E. R. *J. Org. Chem.* **1991**, *56*, 2489−2498. (f) Mikami, K.; Takahashi, O.; Fujimoto, K.; Nakai, T. *Synlett* **1991**, 629. From silyl enol ethers: (g) Reference 21a. (h) Chan, T. H.; Brook, M. A. *Tetrahedron Lett.* **1985**, *26*, 2943−2946.

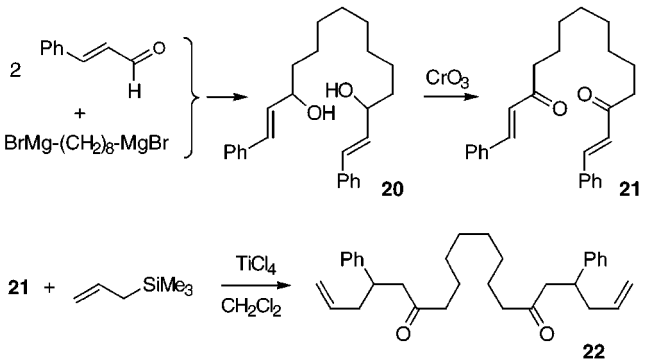
complex with $TiCl_4$[25] which leads to a *Z*-titanium enolate by allylsilane addition.[26]



In a last experiment, BISTRO (0.75 equiv) was added instead of allyltrimethylsilane. After 18 h, the ^{13}C NMR spectrum was recorded and signals at 169.0, 168.6 [C(2) or C(11)], and 118.8 [(C(3) and C(10)] ppm were observed and can be attributed to the cyclic dienolate **19**. With the knowledge of the stereochemistry of the four chiral centers in the diketone **3a**, we can now propose the transition state **16** built with the 2:1 complex (in the course of the addition of BISTRO to benzalacetone, if only 0.5 equiv of $TiCl_4$ was used instead of 1.3 equiv it does not change the stereoselectivity of the reaction, but the yield in **3a** decreases from 74% to 44%). The staggered transition state involved in **16** has an antiperiplanar structure for the (*Z*)-allylsilane moiety and a synclinal structure for the (*E*)-allylsilane one.[27] As the BISTRO **1ct** is more reactive than the **1cc** counterpart, the first step was the addition of the (*E*)-allylsilane moiety leading to the titanium enolate **17**. To determine the structures of the benzalacetone-Lewis acid complex or 3-penten-2-onem−Lewis acid complex and the resulting enolates or dienolates, we have calculated the geometries of the corresponding $SnCl_4$ derivatives by using the semiempirical PM3 SCF-MO method.[28−30] The calculated geometry of the 2:1 benzalacetone−$SnCl_4$ complex confirmed that the s-cis conformation with the two enone molecules is nearly symmetrical with respect to the C2 axis of $SnCl_4$ group ($\Delta H_f = -123.1$ kcal/mol).[30] Calculations confirm that for the β-silyl cation, which constitutes the first intermediate of the addition of BISTRO to **8a**, the structure **17a** (with Sn, $\Delta H_f = -253.5$ kcal/mol), arising from **1ct**, is more stable than the structure **18a** (with Sn, $\Delta H_f = -249.6$ kcal/mol) coming from **1cc**.[31] Similarly, molecular mechanics calculations concerning **17b** and **18b** confirm the relative stability of **17b** (**17b**, $E = 9.68$ kcal/mol; **18b**, $E = 14.20$ kcal/mol).



With the aim of obtaining cyclized compounds, we carried out the addition of BISTRO to the diketone **21** coming from the oxidation of the diol **20**. Significantly, **21** is recovered unchanged. Moreover, the addition of allylsilane occurred with low yield (**22**, 32%). So, we investigated the complexation between **21** and $TiCl_4$. Actually the ^{13}C NMR spectra of the 1:1 complex was the same as the 2:1 **2a**−$TiCl_4$ complex.



Conclusion

The stereoselective reaction of cisoid α,β-unsaturated ketone−titanium complexes with BISTRO **1ct** constitutes a particular molecular recognition phenomenon.[32] In this way, the 3,8-disubstituted-4,7-divinyl-1,10-alkanedione framework, of versatile interest, can be obtained with high stereoselectivity in one step.

Experimental Section

General. All reactions were run under argon in oven-dried glassware. TLC was performed on silica gel 60 F_{254}. ^1H and

(23) For the use of difference NOE experiments to assign the geometry of trimethylsilyl enol ethers, see: (a) Reference 18. (b) Keller, T. H.; Neeland, E. G.; Weiler, L. *J. Org. Chem.* **1987**, *52*, 1870−1872. (c) Bergdahl, M.; Lindstedt, E.-L.; Nilsson, M.; Olsson, T. *Tetrahedron* **1989**, *45*, 535−543.

(24) During the course of the titanium exchange, the isomeric ratio remained virtually unchanged, see ref 21a.

(25) The complexation of 2-butenylalkyl ketones with $SnCl_4$ or $TiCl_4$ led to 2:1 complexes with s-cis conformation, see: Fukuzumi, S.; Okamoto, T.; Fujita, M.; Otera, J. *J. Chem. Soc., Chem. Commun.* **1996**, 393−394.

(26) Silylation of the enolate derived from the conjugate addition of a silyl or methyl group to benzalacetone gave the (*Z*)-enol ether, see: (a) Bernhard, W.; Fleming, I.; Waterson, D. *J. Chem. Soc., Chem. Commun.* **1984**, 28−29. (b) Reference 23c.

(27) Allylsilanes undergo electrophilic substitution reactions regiospecifically in the S_E2' sense and stereospecifically in an anti sense, see: Fleming, I. *J. Chem. Soc., Perkin Trans. 1* **1992**, 3363−3369 and references therein. The anti periplanar transition state for intermolecular additions was originally proposed by Yamamoto, see ref 12l. The intramolecular addition reaction of allylsilanes to aldehydes occurred from synclinal and antiperiplanar transition states with a syn selectivity (47−99%) with a strong dependence on the nature of the Lewis acid, see: Denmark, S. E.; Henke, B. R.; Weber, E. *J. Am. Chem. Soc.* **1987**, *109*, 2512−2514.

(28) The semiempirical PM3 SCF-MO method is not available to titanium.

(29) No addition of BISTRO to benzalacetone was observed when $SnCl_4$ is used as catalyst.

(30) 2:1 complex of ethyl cinnamate with $SnCl_4$ displays an octahedral geometry with Sn at the center of inversion, see: Lewis, F. D.; Oxman, J. D.; Huffman, J. C. *J. Am. Chem. Soc.* **1984**, *106*, 466−468.

(31) PM3 method calculations show that **1ct** and **1cc** have comparable stabilities (**1ct** or **1cc**, $\Delta H_f = -84.64$ kcal/mol).

(32) Reetz, M. T. *Pure Appl. Chem.* **1996**, *68*, 1279−1283.

^{13}C NMR spectra were recorded in $CDCl_3$ solutions at 400, 200 and 100, 50 MHz, respectively. Carbon−proton couplings were determined by DEPT sequence experiments.[33] Diastereoselectivity was determined by GC or ^1H NMR analyses prior to any purification.

Materials. Commercially available unsaturated ketones were distilled or crystallized before use. BISTRO was prepared according to the previously described procedure.[6a] The spectral properties are as follows: IR (gas) 3015, 2962, 1255, 1159, 852 cm^{-1}, (*Z*)-isomers 695 cm^{-1}, (*E*)-isomers 964 cm^{-1}; ^1H NMR δ 5.5−5.3 (m), 2.12 (d, J = 7.9 Hz), 1.57−1.47 (m), 0.09 (s), 0.07 (s). ^{13}C NMR (*Z*,*Z*)-isomer δ 127.3 (d), 125.7 (d), 27.4 (t), 18.6 (t), −1.66 (q); (*Z*,*E*)-isomer δ 128.6 (d), 127.5 (d), 126.3 (d), 125.5 (d), 33.1 (t), 27.7 (t), 22.7 (t), −1.6 (q), −1.8 (q); ^{29}Si NMR δ TMS (*Z*,*Z*)-isomer 1.20, (*Z*,*E*)-isomer 1.25, 0.44.

General Procedure for Sakurai Reaction of 1 with α,β-Enones. A three-necked flask equipped with a thermometer, septum cap, magnetic stirring bar, and argon outlet was charged with anhydrous CH_2Cl_2 (10 mL) and dry nitromethane (0.9 mL, 16 mmol). The solution was cooled to −60 °C, and $TiCl_4$ (0.57 mL, 5.2 mmol) and then α,β-enones (4 mmol) in CH_2Cl_2 (2 mL) were added. The mixture was stirred 0.5 h at −60 °C and then cooled to −90 °C. A solution of BISTRO **1** (2.54 g, 10 mmol) in CH_2Cl_2 (5 mL) was slowly added. The solution was stirred at −90 °C for 0.5 h and then at −60 °C for 12 h. The reaction was quenched by addition of an aqueous saturated NH_4Cl solution (30 mL) and extracted with CH_2Cl_2 (3 × 25 mL). The extracts were stirred with a saturated $NaHCO_3$ solution, dried over $MgSO_4$, and concentrated under vacuum. The residue was chromatographed on silica gel eluting with a gradient of pentane−ether.

Alkylation of Benzalacetone (2a). (4*S,5*R**,8*S**, 9*R**)-4,9-Diphenyl-5,8-divinyldodecane-2,11-dione (3a)** was prepared by addition of **1** to **2a** (584 mg). **3a:** mp 126−127 °C; IR (CCl_4) 2935, 1720, 1165, 1010 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.22 (4, t, J = 7.5 Hz), 7.15 (2, m), 7.04 (4, d, J = 7.5 Hz), 5.32 (1, ddd, J = 17.1, 10.1, 9.9), 5.28 (1, ddd, J = 17.1, 10.1, 9.9), 5.0 (1, d, J = 10.1 Hz), 4.97 (1, d, J = 10.1 Hz), 4.86 (2, d, J = 17.1 Hz), 3.17 (2, m, $W_{1/2}$ = 12.4 Hz), 2.82−2.67 (4, m), 2.15−2.0 (2, m), 2.0 (6, s), 1.38−1.25 (2, m), 1.4−0.92 (2, m); ^{13}C NMR δ 207.6 (s), 141.2 (s), 141.1 (s), 139.3 (d), 139.1 (d), 128.7 (d), 128.6 (d), 127.7 (d), 126.2 (d), 116.6 (t), 116.5 (t), 48.6 (d), 47.9 (d), 47.3 (t), 47.1 (t), 44.3 (d), 44.1 (d), 30.5 (q); mass spectrum, *m*/*z* 402 (0.13), 384 (1.4), 344 (1.8), 274 (2.7), 238 (3.5), 197 (7), 184 (8), 147 (28), 43 (100); HRMS calcd for $C_{28}H_{34}O_2$ 402.2558, found 402.2568. **(4*S**,5*R**)-4-Phenyl-5-vinyldec-9-en-2-one (4a):** IR (neat) 3085, 3040, 1720, 1170, 915, 705 cm^{-1}; ^1H NMR δ 7.33−7.12 (5, m), 5.86−5.67 (1, m), 5.56−5.28 (2, m), 5.12−4.85 (3, m), 3.29 (1, q, J = 4.8 Hz), 2.85 (2, t, J = 6.9 Hz), 2.23 (1, m), 2.07 (3, s), 1.98 (2, m), 1.5−1.1 (4, m); ^{13}C NMR δ 206.5 (s), 143.1 (s), 139.0 (d), 138.1 (d), 128.4 (d) (2C), 127.4 (d) (2C), 125.9 (d), 116.2 (t), 114.0 (t), 47.9 (d), 46.8 (t), 43.9 (d), 33.2 (t), 31.7 (t), 30.0 (q), 26.3 (t). Anal. Calcd for $C_{18}H_{24}O$: C, 84.32; H, 6.24. Found: C, 84.44; H, 6.18. **(4*S**,5*S**)-4-Phenyl-5-vinyldec-9-en-2-one (5a):** ^1H NMR δ (in part) 1.96 (3, s); ^{13}C NMR δ 207.8 (s), 143.7 (s), 139.1 (d), 138.7 (d), 128.3 (d) (2C), 128.1 (d) (2C), 126.3 (d), 116.7 (t), 114.1 (t), 50.4 (d), 49.5 (t), 45.1 (d), 33.4 (t), 31.7 (t), 30.5 (q), 26.4 (t). **1-(1-Phenyl-3-oxobut-1-yl)-2-((trimethylsilyl)-methyl)-3-vinylcyclopentane (6):** mixture of isomers; IR (neat) 2980, 1715, 1250, 915, 865, 840 cm^{-1}; ^1H NMR δ 7.53−7.36 (5, m), 6.00−5.90 (1, m), 5.21−5.12 (2, m), 3.15−2.85 (2, m), 2.26 (0.35, s), 2.22 (0.88, s), 2.19 (1.77, s), 0.3 (1.05, s), 0.27 (2.65, s), 0.9 (5.3, s); ^{13}C NMR (major isomer) δ 207.8 (s), 144.1 (s), 140.2 (d), 128.7 (d), 128.3 (d), 128.0 (d), 114.6 (t), 51.8 (d), 47.1 (d), 46.8 (t), 44.4 (d), 42.9 (d), 30.5 (q), 29.4 (t), 26.8 (t), 16.8 (t), −0.8 (q). Anal. Calcd for $C_{21}H_{32}OSi$: C, 76.77; H, 9.82. Found: C, 76.73; H, 9.80.

NMR of Benzalacetone in the Presence of $TiCl_4$. To an oven-dried 10-mm NMR tube was added a solution of benzalacetone (22 mg, 0.15 mmol) in CD_2Cl_2 (0.5 mL). The tube was equipped with a septum, and an argon atmosphere was established through 2 needles. The tube was cooled at −60 °C, and $TiCl_4$ (4.1 μL, 0.25 equiv) was added via a syringe. The sample was mixed and then placed in the probe (−60 °C) of a Bruker AM 400. After the spectra were recorded, the sample was removed from the probe and placed in a −60 °C bath. Additional quantities of $TiCl_4$ or nitromethane (32.5 μL, 4 equiv) were added via a syringe. In an another experiment, an argon atmosphere was established in a capped empty tube. The tube was cooled at −60 °C, and $TiCl_4$ was added via a syringe followed by the addition of a solution of benzalacetone in CD_2Cl_2. **(*E*)-4-Phenyl-3-buten-2-one (2a):** ^{13}C NMR (0.3 M, CD_2Cl_2, −60 °C, δ 53.8) δ 199.7 (s), 144.0 (d), 134.1 (s), 130.9 (d), 129.3 (d) (2C), 128.5 (d) (2C), 127.1 (d), 27.6 (q); ^1H NMR (0.3 M, CD_2Cl_2, −60 °C) δ 7.59−7.56 (3, m), 7.49 (1, d, J = 16.5 Hz), 7.40 (2, m), 6.68 (1, d, J = 16.5 Hz), 2.36 (3, s). **Bis[(*E*)-4-Phenyl-3-buten-2-one]-titanium tetrachloride:** ^{13}C NMR (0.3 M, CD_2Cl_2, −60 °C, δ 53.8) δ 211.5 (s) ($\Delta\delta$ = 11.8), 155.7 (br signal, w = 0.4) ($\Delta\delta$ = 11.7), 134.0 (s) $\Delta\delta$ = -0.1), 132.9 (d) ($\Delta\delta$ = 3.6), 130.5 (d) ($\Delta\delta$ = 2.0), 129.7 (d) ($\Delta\delta$ = 2.6), 125.7 (br signal, w = 0.5−0.7) ($\Delta\delta$ = −5.2), 26.0 (br signal, w = 0.5−0.7) ($\Delta\delta$ = −0.6); ^1H NMR (CD_2Cl_2, −60 °C) δ 8.04 (1, d, J = 16.1 Hz) ($\Delta\delta$ = 0.55), 7.64 (2, d, J = 7.4 Hz), 7.54 (1, t, J = 7.1 Hz), 7.43 (2, t, J = 7.3 Hz), 7.25 (1, d, J = 16.1 Hz) ($\Delta\delta$ = 0.57), 2.85 (3, s) ($\Delta\delta$ = 0.49). Nitromethane (2 or 4 equiv) in the presence of benzalacetone (1 equiv) and $TiCl_4$ (0,5 or 1 equiv): ^{13}C NMR δ 63.6, ^1H NMR δ 4.32.

Addition of Allyltrimethylsilane to Benzalacetone (2a). 4-Phenyl-2-(trichlorotitanoxy)-2,6-heptadiene (13). To an oven-dried NMR tube were added CD_2Cl_2 (0.5 mL) and nitromethane (4 equiv, 32.5 μL), the tube was cooled at −50 °C, and $TiCl_4$ (18 μL, 1.1 equiv), benzalacetone (22 mg, 0.15 mmol, 1 equiv), and allyltrimethylsilane (48 μL, 2 equiv) were successively added. After 18 h, the spectra were recorded. ^{13}C NMR (CD_2Cl_2; −50 °C, δ 53.8) δ 168.8 (s), 143.2 (s), 135.4 (d), 128.5 (d) (2C), 127.3 (d) (2C), 126.4 (d), 120.3 (br d), 116.1 (t), 41.5, 40.9, 19.3 (q); nitromethane; ^{13}C NMR δ 63.0 (q); excess allyltrimethylsilane δ 135.4 (d), 111.9 (t), 24.1 (t), −2.8 (q); chlorotrimethylsilane: δ 2.6 (q). **4-Phenyl-6-hepten-2-one (14):** ^1H NMR δ 7.38−7.13 (5, m), 5.78−5.50 (2, m), 5.05−4.86 (1, m), 3.22 (1, quint, J = 7.1 Hz), 2.75 (2, d, J = 5.7 Hz), 2.35 (2, t, J = 6.9 Hz), 2.01 (3, s); ^{13}C NMR δ 207.4 (s), 143.9 (s), 136.0 (d), 128.3 (d) (2 C), 127.3 (d) (2 C), 126.3 (d), 116.6 (t), 49.2 (t), 40.7 (d), 40.5 (t), 30.5 (q).

4-Phenyl-2-((trimethylsilyl)oxy)-2,6-heptadiene (15). A mixture of **14** (3.55 g, 18.9 mmol), triethylamine (6.4 mL), and chlorotrimethylsilane (2.9 mL) in DMF (10 mL) was refluxed for 15 h. After being cooled to room temperature, the solution was poured in a cold aqueous saturated $NaHCO_3$ solution and then extracted with pentane. The organic layers were successively washed with an acidic solution, a saturated $NaHCO_3$ solution, and then water. The organic layer was dried ($MgSO_4$), and the solution was concentrated under vacuo (0.2 mmHg for one night). The crude product was mainly constituted by a 3.35:1 mixture of (*Z*)- and (*E*)-silyl ethers. ^1H NMR δ 7.32−7.12 (5, m), 5.8−5.6 (1, m), 5.07−4.92 (2, m), 4.88 (*E*-isomer) (0.23, d, J = 9.52 Hz), 4.67 (*Z*-isomer) (0.77, d, J = 9.12 Hz), 3.73 (0.77, br td, J = 8.84, 7.54 Hz), 3.43 (0.23, br td, J = 9.06, 6.02 Hz), 2.50−2.28 (2, m), 1.81 (*Z*-isomer) (2.31, s), 1.75 (*E*-isomer) (0.69, s), 0.16 (9, s); ^{13}C NMR δ 157.3, 146.7, 145.9, 137.2, 136.9, 128.2, 127.5, 125.7, 116.1, 115.6, 112.1, 91.3, 41.64, 41.6, 22.7, 0.78, 0.4.

(4*S,5*S**,8*R**, 9*R**)-4,9-Diphenyl-5,8-divinyl-2,10-dodecadiene-2,11-diol Tetrachlorotitanate (19).** To an oven-dried NMR tube were added CD_2Cl_2 (0.5 mL) and nitromethane (4 equiv, 32.5 μL), the tube was cooled to −50 °C, and $TiCl_4$ (18 μL, 1.1 equiv), benzalacetone (22 mg, 0.15 mmol, 1 equiv), and BISTRO (29 mg, 0.75 equiv) were successively added. After 18 h, the spectra were recorded. ^{13}C NMR (CD_2Cl_2; −50 °C, δ 53.8) δ (in part) 169.0 and 168.6 (s), 118.8 (d), 19.5 and 19.4 (q), **1cc** (recovered) (in part) 26.9 (t), 18.0 (t).

(33) Doddrell, D. M.; Pegg, D. T.; Bendall, M. R. *J. Magn. Reson.* **1982**, *48*, 323−327.

1,14-Diphenyl-1,13-tetradecadiene-3,12-dione (21): mp 95 °C (lit.[34] mp 96 °C); IR 1680, 1655, 1027 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.56 (4, d, J = 3.7 Hz), 7.51 (2, d, J = 16.2 Hz), 7.39 (6, d, J = 3.3 Hz), 6.73 (2, d, J = 16.2 Hz), 2.64 (4, t, J = 7.4 Hz), 1.61 (4, m), 1.31 (8, br s); ^{13}C NMR (CD_2Cl_2, 400 MHz) δ 200.4 (s), 141.8 (d), 134.6 (s), 130.3 (d), 128.9 (d), 128.2 (d), 126.2 (d), 40.8 (t), 29.4 (t), 29.2 (t), 24.2 (t). **[1,14-Diphenyl-1,13-tetradecadiene-3,12-dione]titanium tetrachloride:** ^{13}C NMR (400 MHz, CD_2Cl_2) δ 214.3 (s)($\Delta\delta$ = 13.9), 156.4 (d) ($\Delta\delta$ = 14.6), 133.2 (s) ($\Delta\delta$ = −1.4), 133.9 (d), 130.5 (d), 129.5 (d), 124.4 (d), 39.6 (t), 28.5 (t), 28.1 (t), 25.7 (t).

Addition of Allyltrimethylsilane to Diketone 21. A three-necked flask equipped with a thermometer, septum cap, magnetic stirring bar, and argon outlet was charged with anhydrous CH_2Cl_2 (2.5 mL) and dry nitromethane (0.11 mL). The solution was cooled to −60 °C, and $TiCl_4$ (0.12 mL, 1.1 mmol) and then diketone **21** (187 mg, 0.5 mmol) in CH_2Cl_2 (2 mL) were added. After a few minutes of stirring, allyltrimethylsilane (0.17 mL, 1.5 mmol) was added. The resulting solution was stirred from −60 °C to −10 °C for 3 h, quenched by addition of an aqueous saturated NH_4Cl solution (3 mL), and then extracted with CH_2Cl_2. The extracts were washed and concentrated under vacuum. The residue was purified by chromatography on silica gel (pentane−ether) to afford the diallyl derivative **22** (74 mg, 32% yield). **4,17-Diphenyl-1,19-eicosadiene-6,15-dione (22):** IR 1720, 1250, 915 cm^{-1}; ^1H NMR δ 7.15 (10, m), 5.60 (2, m), 4.90 (4, m), 3.20 (2, q, J = 7.11 Hz), 2.60 (4, d, J = 6.75 Hz), 2.20 (8, m), 1.30 (4, m), 1.10 (8, m); ^{13}C NMR δ 210.0 (s), 144.1 (s), 136.2 (d), 128.4 (d) (2C), 127.4 (d) (2C), 126.3 (d), 116.7 (t), 48.6 (d), 43.5 (t), 40.8 (t), 40.6 (t), 29.1 (t), 28.9 (t), 23.4 (t). Anal. Calcd for $C_{32}H_{42}O_2$: C, 83.79; H, 9.23. Found: C, 83.82; H, 9.20.

Attempt To Add BISTRO to Diketone 21. The same procedure was applied unsuccessfully to BISTRO (280 mg, 1.1 mmol) instead of allyltrimethylsilane. The reaction mixture was stirred at −60 °C for 24 h and then at 20 °C for 1 h. The diketone **21** was completely recovered.

Acknowledgment. We are indebted to Dr. R. Faure for his assistance in NMR measurements.

JO971677G

(34) Nimgirawath, S.; Ritchie, E.; Taylor, W. C. *Aust. J. Chem.* **1973**, *26*, 183−193.