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A Novel [5+2] Cycloaddition Reaction Using a Dicobalt Acetylene Complex

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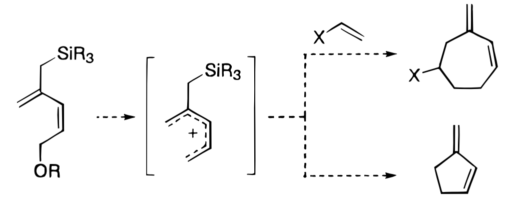
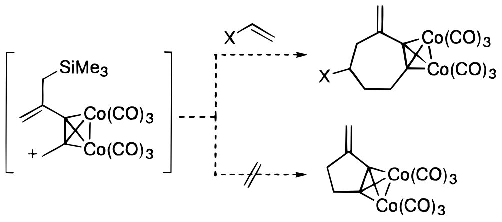
Cycloheptane derivatives are found in a wide range of natural products,[1] and various synthetic methods of these compounds have been explored.[2] From the viewpoint of efficiency, a cycloaddition approach which produces two C−C bonds in one stage is advantageous. In this regard, [4+3]-type annulation reactions of dienes and allyl cationic species have been widely examined,[3] while much less attention has been given to a [5+2] cycloaddition approach.[4−6]

In relation with the [3+2] cycloaddition reactions using a 3-(alkylthio)allyl cationic species as a three-carbon unit,[7] we have been interested in a [5+2] type cycloaddition reaction using a vinylogue of the allyl cationic species. However, there are serious problems in using a pentadienyl cation as a five-carbon unit, that is, (1) the geometry of the pentadienyl cation should be controlled as (*Z*) and (2) the pentadienyl cation with cis configuration would undergo an intramolecular cyclization reaction to give a cyclopentene derivative (Scheme 1).[8] The most reasonable and practical solution to these problems is the use of an oxidopyrylium as a five-carbon unit,[5] which was employed in total synthesis of some natural products.[9]

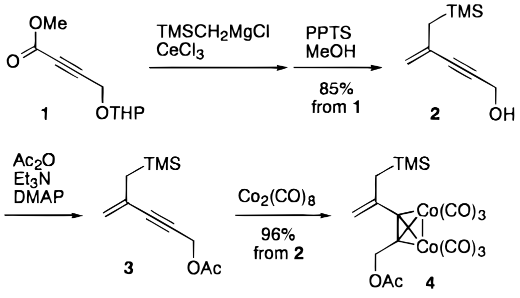
Scheme 1



Scheme 2



Scheme 3



On the other hand, we have reported a powerful methodology for constructing a highly strained ingenane skeleton on the basis of a "tandem cyclization−rearrangement strategy".[10] In this novel transformation, use of a hexacarbonyldicobalt acetylene complex, which has considerably large C(acetylenic)−C(acetylenic)−C(propargylic) angles,[11] was quite effective for selective cyclization to a seven-membered ring.[12] These results led us to design a new [5+2] cycloaddition reaction using a hexacarbonyldicobalt propargyl cation[13] as an equivalent of a pentadienyl cation (Scheme 2).

The five-carbon unit was prepared from ester **1**[14] as shown in Scheme 3. Several enol triisopropylsilyl ethers[15] were subjected to the [5+2] cycloaddition reaction with **4**, and the desired

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(6) Stepwise cycloaddition reactions of "allylsilane-acetal bifunctional reagents" with enol silyl ethers including [5+2]-type annulation were reported: (a) Lee, T. V.; Boucher, R. J.; Rockell, C. J. M. *Tetrahedron Lett.* **1988**, *29*, 689−692. (b) Lee, T. V.; Boucher, R. J.; Porter, J. R.; Rockell, C. J. M. *Tetrahedron* **1989**, *45*, 5887−5894. (c) Lee, T. V.; Cregg, C. *Synlett* **1990**, 317−319.

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(12) For selected examples of seven-membered dicobalt acetylene complexs, see: (a) Schreiber, S. L.; Sammakia, T.; Crowe, W. E. *J. Am. Chem. Soc.* **1986**, *108*, 3128−3130. (b) Yenjai, C.; Isobe, M. *Tetrahedron* **1998**, *54*, 2509−2520. (c) Brook, M. A.; Urschey, J.; Stradiotto, M. *Organometallics* **1998**, *17*, 5342−5346. (d) Patel, M. M.; Green, J. R. *Chem. Commun.* **1999**, 509−510. (e) Iwasawa, N.; Satoh, H. *J. Am. Chem. Soc.* **1999**, *121*, 7951−7952.

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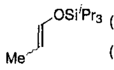
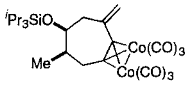
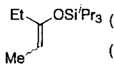
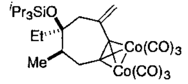
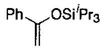
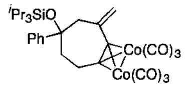
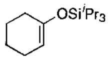
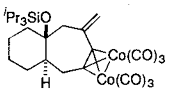
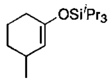
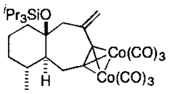
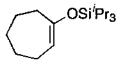
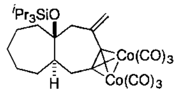
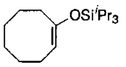
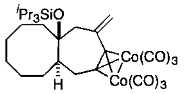
(15) The yield of the cycloadducts depends on the bulkiness of the silyl group. For example, the reaction of 1-(trimethylsiloxy)cyclohexene afforded the desired product in only 12% yield.

10.1021/ja001003e CCC: $19.00

Table 1. [5+2] Cycloaddition Reaction of Enol Silyl Ethers

entry	enol silyl ether	method[a]	product[b]		%yield	ratio[c]
1	 (*Z*)	A		5	98	81:19
2	(*E*)	A			84	83:17
3	 (*Z*)	A		6	75	98:2
4	(*E*)	A			76	98:2
5		B		7	72	-
6		A		8	83	single isomer
7		A		9	88	single isomer
8		B		10	67	97:3
9		B		11	63	single isomer

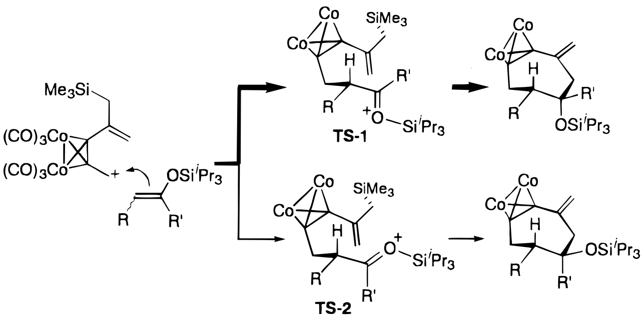
[a] Method A: A mixture of an enol silyl ether and 1.2 equiv of **4** in CH_2Cl_2 was treated with 2.4 equiv of Me_2AlCl at −23 °C. Method B: A mixture of an enol silyl ether and 1.2 equiv of **4** in $ClCH_2CH_2Cl$ was treated with 2.4 equiv of Et_2AlI at −23 °C. [b] Structures of major diastereomers are depicted. [c] Diastereomeric ratio determined by proton NMR spectra.

cycloadducts were obtained in good to high yields (Table 1). In certain cases (entries 5, 8, and 9), use of Et_2AlI in place of Me_2AlCl proved to give better results.

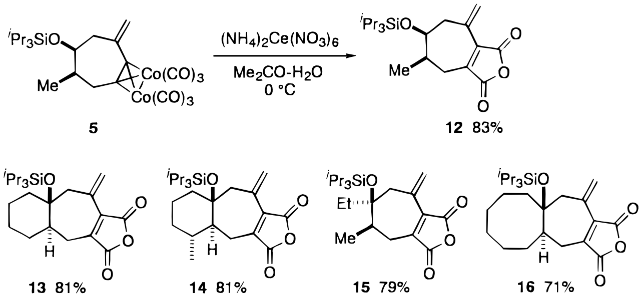
Several stereochemical features of the reactions have been noted:[16] (1) Both of the geometrical isomers of 1-(triisopropylsiloxy)propene afforded the same diastereomer **5** as a major product (entries 1 and 2), and similar behavior was observed in the reactions of 3-(triisopropylsiloxy)-3-pentene (entries 3 and 4). (2) Cyclic enol silyl ethers afforded the corresponding trans-fused bicyclic compounds predominantly. (3) Complete diastereofacial selection was achieved by a methyl group at the allylic position of the cyclohexene ring (entry 7).

Such high stereoselectivity of the [5+2] cycloaddition reaction is remarkable enough to attract much attention from both the synthetic and mechanistic viewpoints. Since the annulation reaction proceeds in a stepwise fashion involving a silyloxonium ion intermediate, the stereochemistry of the products should be determined in the intramolecular cyclization step. Taking into account the rigidity as well as the bulkiness of the dicobalt hexacarbonyl acetylene moiety, two transition state models, in which the acetylene complex moiety is perpendicular to the silyloxonium ion moiety, can be depicted (Scheme 4). In these models, the antiperiplanar transition state (**TS-1**) may be favored over the synclinal transition state (**TS-2**) because of the greater orbital overlap between the oxonium ion and the allylsilane moiety.[17,7a] It should be noted that the configuration of the major product is consistent with **TS-1** in the reactions of both acyclic and cyclic enol silyl ethers.

Scheme 4



Scheme 5



5 **12** 83%

13 81% **14** 81% **15** 79% **16** 71%

While ceric ammonium nitrate (CAN) is generally used to regenerate an alkyne from the corresponding dicobalt hexacarbonyl complex,[18] it is not the case for these cycloaddition products. Thus, treatment of acetylene complex **5** with an excess amount of CAN in acetone−water yielded a maleic anhydride derivative in good yield.[19] This novel transformation involves incorporation of two carbonyl groups on both of the acetylenic carbons, but the reaction mechanism is not clear at this point.

In conclusion, a [5+2] cycloaddition reaction of a new five-carbon unit with an enol silyl ether was developed on the basis of a dicobalt hexacarbonyl propargyl cation species. The high stereoselectivity of the cycloaddition reaction as well as the novel transformation of the cyclization product show promise for natural product synthesis.

Acknowledgment. This work was partially supported by grants from the Ministry of Education, Science, Sports, and Culture of the Japanese Government.

Supporting Information Available: Experimental procedures and characterization data for **2**−**16** and ORTEP drawings of **14** and **16**; ORTEP drawings of the derivative of **12** and **15** (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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[16] The stereochemistry of **5**, **6**, **9**, and **11** was established by X-ray crystallographic structure determination of the corresponding derivatives (Supporting Information). The stereochemistry of **8** and **10** was suggested from the analogy to that of **9** and **11**.

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[18] Seyferth, D.; Nestle, M. O.; Wehman, A. T. *J. Am. Chem. Soc.* **1975**, *97*, 7417−7426.

[19] A similar transformation of an acyclic acetylene dicobalt hexacarbonyl complex was reported: Schottelius, M. J.; Chen, P. *Helv. Chim. Acta* **1998**, *81*, 2341−2347.