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$W(CO)_5(L)$-Catalyzed Tandem Intramolecular Cyclopropanation/Cope Rearrangement for the Stereoselective Construction of Bicyclo[5.3.0]decane Framework

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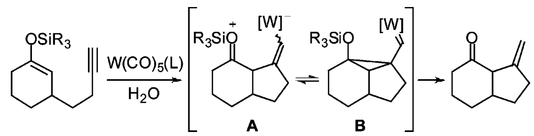
In this paper, we report a facile method for the stereoselective construction of the bicyclo[5.3.0]decane skeleton from 3-siloxy-1,3,9-trien-7-ynes through divinylcyclopropane intermediates based on the $W(CO)_5(L)$-catalyzed electrophilic activation of alkynes as a biscarbene equivalent.

During the study on the $W(CO)_5(L)$-catalyzed cyclization of ω-acetylenic silyl enol ethers,[1] we analyzed the structure of the zwitterionic addition intermediate **A** by calculation and found that cyclopropyl carbene structure **B** is favorable in the gas phase (Scheme 1).[2,3] In this reaction, protonation occurs through the zwitterionic intermediate **A** to give the cyclized product;[1b] however, it is expected that cyclopropyl carbene intermediate **B** could be utilized for further reaction provided that a process with a low activation energy is feasible through this intermediate. It is well-known that the Cope rearrangement of divinylcyclopropanes occurs rapidly at room temperature to form a seven-membered ring system.[4] We then expected that treatment of 3-siloxy-1,3,9-trien-7-ynes with $W(CO)_5(L)$ would give zwitterionic intermediates **C** and/or divinylcyclopropane carbene complex intermediates **D** (Scheme 2), and that the Cope rearrangement of the latter would occur smoothly to give synthetically useful functionalized bicyclo-[5.3.0]decane derivatives stereoselectively.

We first examined the reaction of enyne **1a** with 10 mol % of preformed $W(CO)_5(thf)$ in THF in the presence of MS 4Å (Table 1, entry 1). The reaction proceeded as expected, and the desired seven-membered ring product **2a** was obtained in 78% yield as a single stereoisomer after 13 h at 60 °C. The structure of **2a** was confirmed by X-ray analysis, and its relative stereochemistry can be explained by the transition-state model of the Cope rearrangement of divinylcyclopropanes as shown in **X**.[4] When the reaction was carried out in toluene under photoirradiation, only 5 mol % of $W(CO)_6$ was sufficient to complete the reaction within 2 h at room temperature, and **2a** was obtained in 66% yield (entry 2).[5] In addition, by carrying out the same reaction in the presence of 10 mol % of NEt_3, the yield of **2a** was further improved to 83% (entry 3).[5] Some other transition-metal catalysts, such as Re, Pt, and Au,[6] were also examined (entries 4−7), but $W(CO)_5(L)$ was found to be the most suitable catalyst for this reaction.

Having established that $W(CO)_5(L)$ efficiently catalyzed the seven-membered ring formation, the reaction was examined employing several types of substrates with the results being summarized in Table 2. Vinylic (**1b**) and monosubstituted enynes (**1c**, **1d**) were cyclized to afford the corresponding bicyclic enol silyl ethers in good yield as a single stereoisomer (entries 1−3). It should be noted that the reaction of **1c** having a (*Z*)-propenyl moiety at the alkyne terminus afforded the bicyclic product **2c**, the relative stereochemistry of which was different from that of **2a** derived from (*E*)-propenyl derivative **1a** (Table 1, **1a** vs Table 2, entry 2, **1c**). These results strongly suggest that this reaction is a concerted reaction and is really proceeding through divinylcyclopropane

Scheme 1



Scheme 2

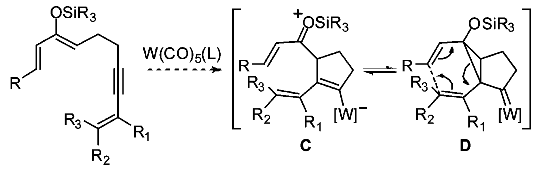
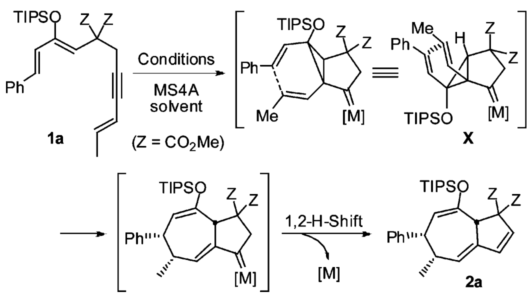


Table 1. Reaction of Dienol Silyl Ether **1a**



entry	conditions	time (h)	yield (%)
1	10 mol % of $W(CO)_5(thf)$/THF, 60 °C	13	78
2	5 mol % of $W(CO)_6$, $h\nu$/toluene, rt	2	66
3[a]	5 mol % of $W(CO)_6$, $h\nu$/toluene, rt	2	83
4	5 mol % of $ReCl(CO)_5$, $h\nu$/toluene, rt	34	4
5	5 mol % of $PtCl_2$/toluene, 70 °C	17	12
6	5 mol % of AuCl/toluene, 70 °C	3	54
7	5 mol % of $Ph_3PAu(SbF_6)$/DCE, 70 °C	6	0

[a] In the presence of 10 mol % of NEt_3.

intermediates (Scheme 2). Furthermore, the reaction of disubstituted enyne (**1e**), an enyne bearing an acetal moiety (**1f**), and alkyl-substituted dienes (**1g**, **1h**) also underwent seven-membered ring formation smoothly in good yields using only a catalytic amount of $W(CO)_6$ (entries 4−7).

We next applied this reaction to a concise synthesis of tricyclic compounds possessing a seven-membered ring moiety. The reaction of dienol silyl ethers having a cyclohexenyl group at the alkyne terminus (**3**) or as part of the diene moiety (**5**) with a catalytic amount of $W(CO)_6$ and 10 mol % of NEt_3 in toluene under photoirradiation gave the tricyclic compounds **4** and **6** in good yields stereoselectively (eqs 1 and 2).

Recently, we reported related tungsten(0) or rhenium(I)-catalyzed tandem cyclization of 3-siloxy-1,3-dien-7-ynes to give bicyclo[3.3.0]-octane derivatives as a mixture of diastereomers, which are thought

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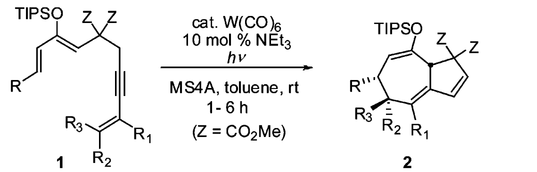
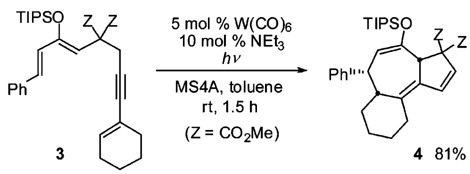
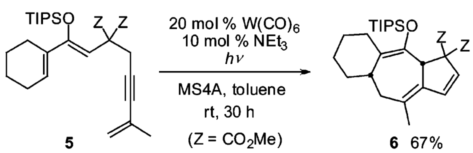
Table 2. W(CO)$_5$(L)-Catalyzed Reaction of Dienol Silyl Ethers **1b**−**1h**



entry	R	(R_1,R_2,R_3)		W(CO)$_6$ (mol %)	yield(%)
1[a]	Ph		**1b**	10	63
2			**1c**	5	80
3			**1d**	5	79
4			**1e**	5	78
5[a]		MeO, OMe (*E* : *Z* = 6 : 1)	**1f**	5	71[b]
6	*i*-Pr		**1g**	5	83
7			**1h**	10	61

[a] In the absence of NEt_3. [b] The product was obtained as a 6:1 mixture of diastereomers.

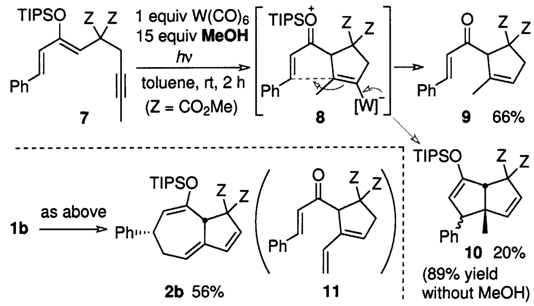

(1)


(2)

to be obtained in a stepwise tandem-cyclization manner (see Scheme 3).[7] On the contrary, we believe that the present reaction proceeds through a divinylcyclopropane intermediate based on the following experimental results: (1) While bicyclo[3.3.0]octanes were prepared as a mixture of diastereomers, bicyclo[5.3.0]decanes were obtained as a single stereoisomer stereospecifically. It is unlikely that the second cyclization step of dienyltungsten species (see **C** in Scheme 2) onto an α,β-unsaturated silyloxonium moiety occurs with perfect stereoselectivity. (2) Reactions in the presence of a proton source afforded different results (Scheme 3). In the reaction of **7** with 1 equiv of W(CO)$_6$ and 15 equiv of MeOH in toluene under photoirradiation, monocyclic ketone **9**, the protonated product of the first cyclization intermediate **8**, was obtained in 66% yield as a major product. Under the same conditions, bicyclic silyl enol ether **2b** was obtained in 56% yield without formation of monocyclic derivative **11** in the reaction of enyne **1b**. (3) The reaction of 1,3,9-trien-7-ynes **1** is much faster than that of 1,3-dien-7-ynes **7**. For example, the reaction of enyne **1a** was completed in 2 h (Table 1, entry 2), while the reaction of alkyne **7** was completed in 7 h under the same conditions.[8] All of these results strongly suggest that the five-membered ring formation proceeds in a stepwise manner, while the seven-membered ring formation proceeds in a different, concerted manner.

In almost all of the previous cases, the divinylcyclopropanes have been prepared by the Rh-catalyzed cyclopropanation of dienes with unsaturated diazo compounds, which are not necessarily easy to handle.[9,10] In the present reaction, alkynes behave as a biscarbene equivalent by transition-metal activation, and bicyclo[5.3.0]decane derivatives can be synthesized in a single step from easily available alkynes without the use of diazo compounds.[11]

Scheme 3



In summary, we have developed W(CO)$_5$(L)-catalyzed tandem intramolecular cyclopropanation/Cope rearrangement of 3-siloxy-1,3,9-trien-7-ynes. This reaction provides a new, concise approach for the stereoselective synthesis of synthetically useful functionalized bicyclo[5.3.0]decane derivatives, which constitute the basic carbon skeleton of many natural products.

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Supporting Information Available: Preparative methods and spectral and analytical data of compounds **1**−**6** (PDF) and X-ray data for **2a**, *cis*-**2f**, and **4** (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

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(5) A small amount of bicyclo[3.3.0]octane derivative was obtained in 3% yield (entry 2) and 4% yield (entry 3).
(6) In the case of cationic gold complex (entry 7), protonated product of the first cyclization intermediate **C** was obtained in 75% yield.
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