J|A|C|S
COMMUNICATIONS

Novel Approach for Catalytic Cyclopropanation of Alkenes via (2-Furyl)carbene Complexes from 1-Benzoyl-*cis*-1-buten-3-yne

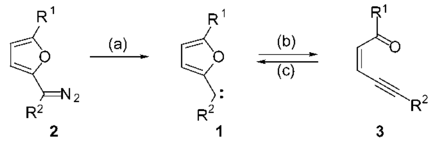
Koji Miki, Fumiaki Nishino, Kouichi Ohe,* and Sakae Uemura*

Department of Energy and Hydrocarbon Chemistry, Graduate School of Engineering, Kyoto University, Sakyo-ku, Kyoto 606-8501, Japan

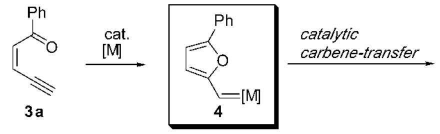
Received February 1, 2002

Despite many attempts to generate 2-furfurylidenes **1** from diazoalkanes **2** by thermolysis and photolysis (Scheme 1, step a), they are formidably difficult to trap due to their high reactivity, which causes rapid rearrangement (coarctate reaction) to ring-opened product **3** (Scheme 1, step b).[1,2] Recently, it has been reported that unique photocyclization of **3** having 1,2-diketone moiety ($R^1 = Ac$, $R^2 = H$ or Ar) affords 2-furfurylidene **1** (Scheme 1, path c), which could be intermolecularly trapped with water or alcohols and intramolecularly trapped by aromatic insertion.[3] Photolytic conditions as well as the inherent nature of **1** prone to rearrangement, however, have prohibited the trapping of **1** with alkenes except for a limited species ($R^2 = Cl$).[4] We have now found the generation of metal complexes of 2-furfurylidene **4** through 5-exo-*dig* cyclization of an ene-yne-ketone **3a** ($R^1 = Ph$, $R^2 = H$) (Scheme 2). In this paper we report novel catalytic cyclopropanation of alkenes on the basis of generation of **4** from **3** and transition metals.

Scheme 1

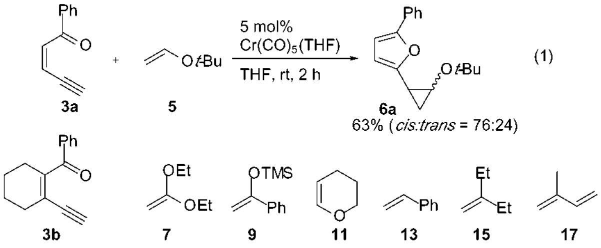


Scheme 2



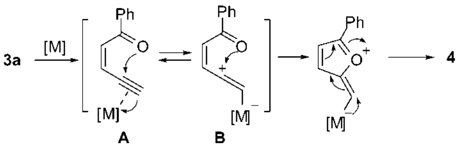
We recently reported that group 6 transition metals undergo pericyclic reactions of ene-yne-esters and -amides **3** ($R^1 = OR$, NR_2; $R^2 = H$) leading to 2-pyranylidene complexes[5] and [3,3]-sigmatropy of 1-acyl-2-ethynylcyclopropanes[6] via vinylidene-metal intermediates, respectively. We also found that ene-yne-ketones **3** ($R^1 = Ar$, $R^2 = H$) react with group 6 metals to give stable (2-furyl)carbene complexes **4**.[7] Complexes **4** are somewhat more stable than nonheteroatom-stabilized phenylcarbene complexes,[8] which could be stoichiometrically generated and used for cyclopropanation.[9] Then, we focused on the catalytic activity of **4** toward alkenes.

At first, the reaction of **3a** with *tert*-butyl vinyl ether (**5**) (2 equiv) was carried out in the presence of 5 mol % of $Cr(CO)_5(THF)$ at room temperature (eq 1). The color of the reaction mixture gradually changed from deep blue to yellowish brown as the reaction proceeded.[10] After 2 h, 1-*tert*-butoxy-2-[(5-phenyl)fur-2-yl]cyclopropane (**6a**) was isolated in 63% yield as a mixture of cis and trans isomers (cis:trans = 76:24). Next, we examined cyclopropanations of several alkenes with ene-yne-ketones **3a** and **3b** in the presence of Cr catalyst. Typical results are given in Table 1.[11] The reaction of **3b** with **5** also gave the cyclopropanated product **6b** (90%, cis:trans = 60:40) (entry 1). Reactions of **3a**,**b** with ketene diethyl acetal (**7**) proceeded quite smoothly to give cyclopropanes **8a** (82%) and **8b** (99%), respectively (entries 2 and 3). Ene-yne-ketone **3b** reacted with enol silyl ether **9** to give **10b** (83%) with a 66:34 diastereomeric ratio (entry 4). The reaction of **3b** with cyclic vinyl ether **11** exclusively gave endo cyclopropanated product **12b** (90%) (entry 5).[12] Styrene (**13**) reacted slowly with **3b** to give **14b** (85%, cis:trans = 74:26), although the reaction required 20 equiv of **13** (entry 6). On the other hand, cyclopropanation of vinyl acetate or 1-octene with **3b** resulted in lower yields, 22% (6 days) and 19% (10 days), respectively, even by use of 20 equiv of the alkene. The cyclopropanation of 2-ethylbut-1-ene (**15**) with **3b** gave **16b** (52%), although prolonged reaction time (96 h) was required (entry 7). In the reactions of isoprene (**17**) with **3a** and **3b**, a more substituted double bond was selectively cyclopropanated to give **18a** (40%) and **18b** (88%) with nondiastereoselective manner, respectively (entries 8 and 9). A higher reactivity of electron-rich alkenes and a slightly preferential formation of *cis*-cyclopropanes indicate that the cyclopropanation proceeds through the formation of an electrophilic (2-furyl)carbene-chromium complex like phenylcarbene-tungsten and -iron complexes.[9]



As shown in Scheme 3, 5-exo-*dig* cyclization of ene-yne-ketone **3**[7] via nucleophilic attack of a carbonyl oxygen to an internal carbon of an alkyne in η^2-alkyne complex **A** might be the most plausible pathway for generation of (2-furyl)carbene-chromium complex **4** ($M = Cr(CO)_5$). It should be noted that a transition metal can promote the cyclization similar to photocyclization of **3** (vide supra).[3] A slipped, polarized η^1-complex **B** would be an alternatively possible intermediate. It is well-known that **A** is prone to isomerize to **B**, which has been widely accepted for cyclization and skeletal reorganization of 1,6-enynes with a diversity of metal complexes.[13]

Scheme 3

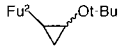
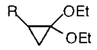
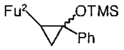
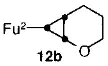
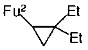
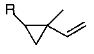


---

* Corresponding author. E-mail: (K.O.) ohe@scl.kyoto-u.ac.jp or (S.U.) uemura@scl.kyoto-u.ac.jp.

10.1021/ja025776+ CCC: $22.00

Table 1. Cr-Catalyzed Cyclopropanation of Alkenes with **3**[a]

entry	3	alkene	time (h)	product	isolated yield	cis:trans
1	**b**	**5**	3	 **6b**	90%	60:40
2	**a**	**7**	1.5	 **8a** (R = Fu^1)	82%	N.A.[b]
3	**b**	**7**	2	**8b** (R = Fu^2)	99%	N.A.[b]
4	**b**	**9**	4	 **10b**	83%	66:34[c]
5	**b**	**11**	22	 **12b**	90%	endo only
6	**b**	**13**[d]	14	 **14b**	85%	74:26
7	**b**	**15**[e]	96	 **16b**	52%	N.A.[b]
8	**a**	**17**[f]	5	 **18a** (R = Fu^1)	40%	50:50
9	**b**	**17**[f]	27	**18b** (R = Fu^2)	88%	50:50

[a] Reactions were carried out at room temperature with **3** (0.50 mmol), alkene (1.0 mmol), and $Cr(CO)_5(THF)$ prepared by irradiating a solution of $Cr(CO)_6$ (0.025 mmol) in THF (2 mL) unless otherwise noted. [b] N.A. = not applicable. [c] Configuration is not yet known. [d] Styrene (10 mmol). [e] 2-Ethylbut-1-ene (7.5 mmol). [f] Isoprene (5.0 mmol).

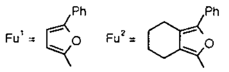
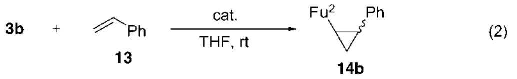


Table 2. Catalytic Cyclopropanation of Styrene (**13**) Using **3b**[a]

entry	catalyst	time (h)	yield (%)[b]	*cis:trans*[c]
1	$Mo(CO)_5(THF)$[d]	2	23	54:46
2	$W(CO)_5(THF)$[d]	2	54	70:30
3	$[RuCl_2(CO)_3]_2$[e]	24	42	12:88
4	$[RhCl(cod)]_2$[e]	2	69	56:44
5	$PdCl_2$	2	79	21:79
6	$PtCl_2$	5	81	23:77

[a] Reactions were carried out at room temperature with **3b** (0.20 mmol), **13** (4.0 mmol), and a catalyst (0.010 mmol) in THF (2 mL) unless otherwise noted. [b] Isolated yield. [c] Determined by ^1H NMR. [d] Prepared by irradiating a solution of $M(CO)_6$ in THF. [e] 0.005 mmol.

Considering the possibility of the intervention of **B**, we examined cyclopropanation of styrene with **3b** in the presence of other transition metal catalysts (eq 2 and Table 2). Other group 6 metal complexes, such as $Mo(CO)_5(THF)$ and $W(CO)_5(THF)$, were also found to catalyze the cyclopropanation to give **14b** in 23% and 54% yields with 54:46 and 70:30 cis and trans ratios, respectively. Of group 8 triad metals, $[RuCl_2(CO)_3]_2$ was moderately effective to yield **14b** (42%, cis:trans = 12:88). Of group 9 triad metals, $[RhCl(cod)]_2$ also gave **14b** (69%, cis:trans = 56:44). $PdCl_2$ and $PtCl_2$ of group 10 triad effectively catalyzed the cyclopropanation to give rise to **14b** in 79% (21:79 ratio) and 81% yields (23:77 ratio), respectively. Among catalysts examined, Cp_2Ti(isobutylene), $Mn(acac)_2$, $NiCl_2$, $CuOTf(^1/_2C_6H_6)$, $Cu(OTf)_2$, and $AuCl_3$ were not effective as catalysts for the present cyclopropanation. Variable stereoselectivity with catalysts indicates that cyclopropanation proceeds in a different manner for each catalyst.[14] The precise mechanism of the cyclopropane formation step is not clear at present and further studies are awaited.



(2)

In conclusion, we have demonstrated new catalytic cyclopropanation of alkenes on the basis of the generation of (2-furyl)carbene complexes from conjugated ene-yne-ketones. This system has wide applicability to a diversity of transition metal complexes as well as a variety of ene-yne-ketones, and may find some applications in other catalytic 2-furfurylidene transfer reactions. These studies are now in progress in our laboratory.

Acknowledgment. This work was supported by Priority Areas (A) "Exploitation of Multi-Element Cyclic Molecules" from the Ministry of Education, Culture, Sports and Technology, Japan.

Supporting Information Available: Experimental procedures and analytical and spectral data for all new compounds (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

References

(1) (a) Hoffman, R. V.; Shechter, H. *J. Am. Chem. Soc.* **1971**, *93*, 5940. (b) Hoffman, R. V.; Orphanides, G. G.; Shechter, H. *J. Am. Chem. Soc.* **1978**, *100*, 7927. (c) Hoffman, R. V.; Shechter, H. *J. Am. Chem. Soc.* **1978**, *100*, 7934. (d) Kirmse, W.; Lelgemann, R.; Friedrich, K. *Chem. Ber.* **1991**, *124*, 1853. (e) Albers, R.; Sander, W. *Liebigs Ann.* **1997**, 897. (f) Sander, W.; Albers, R.; Komnick, P.; Wandel, H. *Liebigs Ann.* **1997**, 901.

(2) Herges analyzed the topology on ring-opening reaction of **1** to **3** and termed it coarctate reaction, see: (a) Herges, R. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 255. For recent theoretical approaches to coarctate reaction of **1**, see: (b) Sun, Y.; Wong, M. W. *J. Org. Chem.* **1999**, *64*, 9170. (c) Birney, D. M. *J. Am. Chem. Soc.* **2000**, *122*, 10917.

(3) (a) Nakatani, K.; Maekawa, S.; Tanabe, K.; Saito, I. *J. Am. Chem. Soc.* **1995**, *117*, 10635. (b) Nakatani, K.; Tanabe, K.; Saito, I. *Tetrahedron Lett.* **1997**, *38*, 1207. (c) Nakatani, K.; Adachi, K.; Tanabe, K.; Saito, I. *J. Am. Chem. Soc.* **1999**, *121*, 8221.

(4) Khasanova, T.; Sheridan, R. S. *J. Am. Chem. Soc.* **1998**, *120*, 233. For 2-benzofurylchlorocarbene, see: Khasanova, T.; Sheridan, R. S. *J. Am. Chem. Soc.* **2000**, *122*, 8585.

(5) Ohe, K.; Miki, K.; Yokoi, T.; Nishino, F.; Uemura, S. *Organometallics* **2000**, *19*, 5525. For benzopyranylidene complexes, see: Iwasawa, N.; Shido, M.; Maeyama, K.; Kusama, H. *J. Am. Chem. Soc.* **2000**, *122*, 10226.

(6) Ohe, K.; Yokoi, T.; Miki, K.; Nishino, F.; Uemura, S. *J. Am. Chem. Soc.* **2002**, *124*, 526.

(7) Miki, K.; Yokoi, T.; Nishino, F.; Ohe, K.; Uemura, S. *J. Organomet. Chem.* **2002**, *645*, 228. For 6-endo-*dig* cyclization of 2-ethynylacylbenzene with $W(CO)_5(THF)$ complex, see: Iwasawa, N.; Shido, M.; Kusama, H. *J. Am. Chem. Soc.* **2001**, *123*, 5814.

(8) (a) Casey, C. P.; Polichnowski, S. W. *J. Am. Chem. Soc.* **1977**, *99*, 6097. (b) Brookhart, M.; Nelson, G. O. *J. Am. Chem. Soc.* **1977**, *99*, 6099. (c) Casey, C. P.; Polichnowski, S. W.; Shusterman, A. J.; Jones, C. R. *J. Am. Chem. Soc.* **1979**, *101*, 7282. (d) Brookhart, M.; Humphrey, M. B.; Kratzer, H. J.; Nelson, G. O. *J. Am. Chem. Soc.* **1980**, *102*, 7802. (e) Doyle, M. P.; Griffin, J. H.; Bagheri, V.; Dorow, R. L. *Organometallics* **1984**, *3*, 53. (f) Fischer, H.; Zeuner, S.; Ackermann, K. *J. Chem. Soc., Chem. Commun.* **1984**, 684. (g) Fischer, H.; Hofmann, J. *Chem. Ber.* **1991**, *124*, 981. (h) Casey, C. P.; Vosejpka, L. J. S. *Organometallics* **1992**, *11*, 738. (i) Fischer, H.; Mauz, E.; Jaeger, M. *J. Organomet. Chem.* **1992**, *427*, 63. (j) Catalytic approach for a 9-(9*H*-fluorenylidene)chromium complex, see: Pfeiffer, J.; Dötz, K. H. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 2828. Pfeiffer, J.; Nieger, M.; Dötz, K. H. *Eur. J. Org. Chem.* **1998**, 1011.

(9) (a) Brookhart, M.; Studabaker, W. B. *Chem. Rev.* **1987**, *87*, 411. (b) Helquist, P. In *Advances in Metal-Organic Chemistry*; Liebeskind, L. S., Ed.; JAI Press: London, 1991; Vol. 2, pp 143−194. (c) Doyle, M. P. In *Comprehensive Organometallic Chemistry II*; Hegedus, L. S., Ed.; Pergamon: Oxford, 1995; Vol. 12, pp 387−420.

(10) The blue color indicates the generation of (2-furyl)carbene chromium complex. Thus, consumption of the starting material **3** could be visibly monitored.

(11) All new compounds obtained gave satisfactory spectral and combustion analytical data.

(12) The structure was unambiguously determined by X-ray diffraction analysis of **12b**. See Supporting Information.

(13) (a) Chatani, N.; Morimoto, T.; Muto, T.; Murai, S. *J. Am. Chem. Soc.* **1994**, *116*, 6049. (b) Chatani, N.; Furukawa, N.; Sakurai, H.; Murai, S. *Organometallics* **1996**, *15*, 901. (c) Chatani, N.; Kataoka, K.; Murai, S.; Furukawa, N.; Seki, Y. *J. Am. Chem. Soc.* **1998**, *120*, 9104. (d) Chatani, N.; Inoue, H.; Morimoto, T.; Muto, T.; Murai, S. *J. Org. Chem.* **2001**, *66*, 4433. (e) Fürstner, A.; Szillat, H.; Gabor, B.; Mynott, R. *J. Am. Chem. Soc.* **1998**, *120*, 8305. (f) Trost, B. M.; Doherty, G. A. *J. Am. Chem. Soc.* **2000**, *122*, 3801. (g) Fernández-Rivas, C.; Méndez, M.; Echavarren, A. M. *J. Am. Chem. Soc.* **2000**, *122*, 1221. (h) Méndez, M.; Muñoz, M. P.; Nevado, C.; Cárdenas, D. J.; Echavarren, A. M. *J. Am. Chem. Soc.* **2001**, *123*, 10511. (i) Martín-Matute, B.; Cárdenas, D. J.; Echavarren, A. M. *Angew. Chem. Int. Ed.* **2001**, *40*, 4754. (j) Oi, S.; Tsukamoto, I.; Miyano, S.; Inoue, Y. *Organometallics* **2001**, *20*, 3704.

(14) Catalysts appear to alter the reaction course via charge-developed intermediates or metallacyclobutane intermediates.

JA025776+