Radical Carbonylation of 1,5-Enynes Using TTMSS as a Chain Carrier. Unexpected Formation of Persistent 3-Silyl-1-siloxyallyl Radicals Serving as a Chain Breaking Path

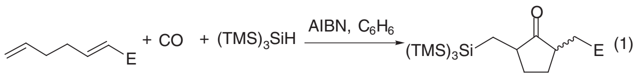
Takahide Fukuyama, Yoshitaka Uenoyama, Shinya Oguri, Noboru Otsuka, and Ilhyong Ryu*
Department of Chemistry, Faculty of Arts and Sciences, Osaka Prefecture University, Sakai, Osaka 599-8531

(Received April 26, 2004; CL-040476)

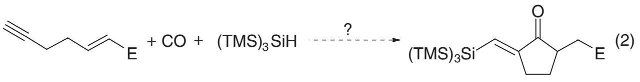
The radical carbonylation of 1,5-enynes **1a** and **1b** using TTMSS as radical mediator gave the predicted carbonylative cyclization products **2a** and **2b**, respectively, in poor yields. The isolation and characterization of reaction byproducts by X-ray crystallographic analysis suggest that the poor chain propagation can be attributed to the formation of long-lived 3-silyl-1-siloxyallyl radicals, produced by the addition of a $(TMS)_3Si$ radical onto the O–C double bond of the initially formed cyclopentanones.

Radical carbonylation reactions have emerged as promising methods for the introduction of carbon monoxide into organic molecules.[1] We previously reported that the cyclizative silylcarbonylation of 1,5-dienes using TTMSS (tris(trimethylsilyl)silane)[2] led to 2-(silylmethyl)cyclopentanones in good yields (Eq 1).[3] The reaction starts with the addition of silyl radical to a diene terminus to form a β-silylalkyl radical, which subsequently undergoes carbonylation, followed by 5-*exo* cyclization. The resulting radical abstracts hydrogen from TTMSS to give the desired cyclopentanone and a $(TMS)_3Si$ radical, which participates in an efficient radical chain propagation. On the basis of these findings, we concluded that a similar $4 + 1$ type radical annulation strategy might also be applicable to the case of 1,5-enynes, in which cyclopentanones having a silylmethylene unit at the α-position would be the likely product (Eq 2). In this letter, we report that, unlike the previous 1,5-diene carbonylation,[3] 1,5-enyne carbonylation by TTMSS suffers from low chain propagation, which is caused by the formation of a long-lived radical, the 3-silyl-1-siloxyallyl radical.

Previous work (Ref. 2):

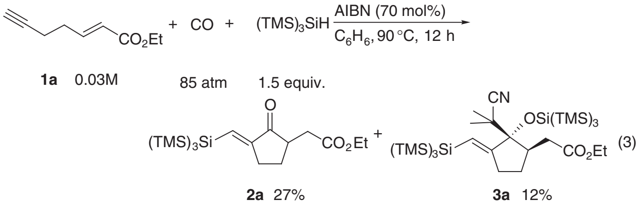


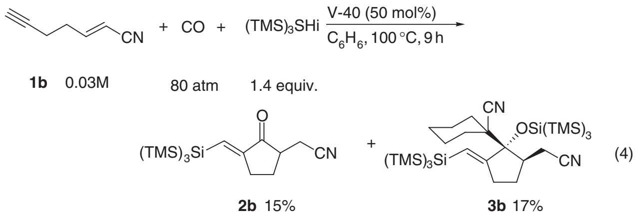
This work:



1a E = CO_2Et
1b E = CN

When Ethyl hept-2-en-6-ynoate (**1a**) was treated with carbon monoxide (85 atm) and tris(trimethylsilyl)silane (1.5 equiv.) in the presence of AIBN (2,2′-azobisisobutyronitrile) as a radical initiator at 90 °C for 12 h, the anticipated α-silylmethylene cyclopentanone **2a** was obtained, but in a very low yield (Eq 3).[4] In this reaction, a significant amount of **1a** remained unreacted, suggesting poor chain propagation. A careful check of the reaction mixture led to the identification of higher molecular weight byproduct. X-ray crystallographic analysis indicated that the structure of the byproduct was **3a**, which is comprised of one molecule of 1,5-enyne **1a**, one molecule of carbon monoxide, two molecules of tris(trimethylsilyl)silyl group, and one molecule of 2-cyanopropyl group (Figure 1).[5] When a similar reaction of hept-2-en-6-ynenitrile (**1b**) was examined, using V-40 [1,1′-azobis(cyclohexane-1-carbonitrile)] as a radical initiator, the desired product **2b** was obtained again in low yield along with an analogous byproduct **3b**, which contained a cyano(cyclohexyl) unit derived from V-40 (Eq 4). When we carried out a similar reaction of **1a** using BPO (benzoyl peroxide), the yield of **2a** increased by as much as 34% without the formation of the related byproduct, however, the remaining, unreacted **1a** suggested that chain propagation was still a limiting factor in the reaction.





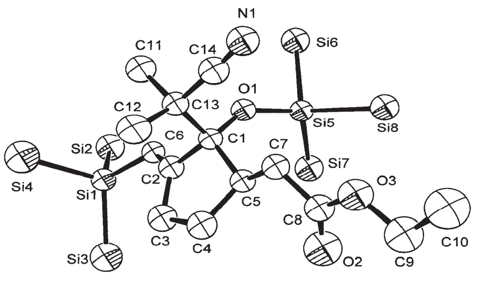
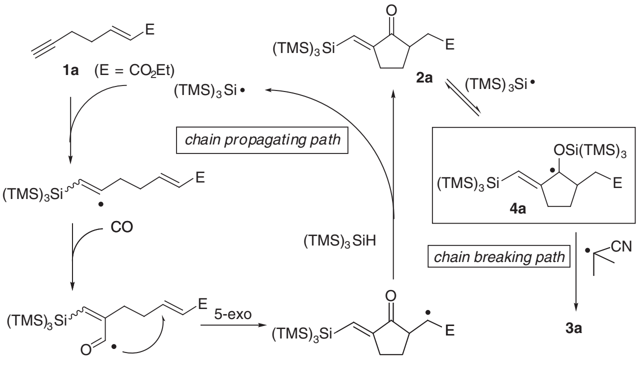


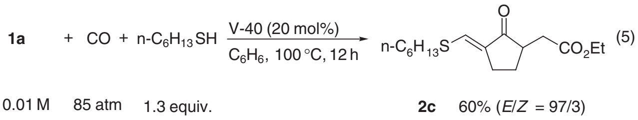
Figure 1. ORTEP drawing of **3a**. Methyl groups on the Si atoms are omitted for clarity.

What we observed here with TTMSS-mediated reactions can be rationalized by assuming two reaction pathways, which are illustrated in Scheme 1. The $(TMS)_3Si$ radical adds to an acetylene terminus of **1a** to form a vinyl radical, which adds to CO to give an α,β-unsaturated acyl radical. The subsequent 5-*exo* cyclization of the acyl radical followed by the abstraction of hydrogen from TTMSS would afford the α-(silylmethylene)cyclopentanone **2a** and $(TMS)_3Si$ radical. The poor chain propagation observed in the present system may be accounted for by the formation of a siloxyallyl radical, **4a**, which can be produced by the trapping of the initial product **2a** by a (TMS)$_3$Si radical.[6] The allyl radical **4a**, protected by two bulky (TMS)$_3$Si group, is hardly quenched by the abstraction of hydrogen from TTMSS. As a result, the radical **4a** diminished by coupling with the 2-cyanoisopropyl radical, which is produced by the thermolysis of the radical initiator, AIBN, to give **3a**.



Scheme 1. Possible reaction pathway for the silylcarbonylation of **1a**.

The formation of a silyloxyallyl radical **4a** is due to the oxophilic nature of the (TMS)$_3$Si radical.[7] For comparison, we examined the similar carbonylation of the 1,5-enyne **1a** using haxanethiol.[8] The expected cyclopentanone **2c** was obtained in 60% yield without contamination by a related coupling product (Eq 5).[9]



In conclusion, the cyclizative radical carbonylation of 1,5-enynes using TTMSS as a mediator leads to the production of 2-(silylmethylene)cyclopentanones. However, the efficiency of the reaction is poor. In this reaction, the β-silyl-substituted enone products serve as a trap for (TMS)$_3$Si radicals, resulting in the formation of persistent 3-sily-1-siloxyallyl radicals, which prevents further chain propagation. In contrast, a similar reaction using hexanethiol as a mediator proceeds well without suffering from such a chain breaking. These results have significant implications for reactions involving (TMS)$_3$Si radicals, since the oxophilic trap of a (TMS)$_3$Si radical may alter the course of the desired propagation reactions.

This work was supported by Grant-in-Aid for Scientific Research (B) from JSPS. We acknowledge Professor Hiroyuki Matsuzaka for his generous help in obtaining the X-ray data for **3a**.

References and Notes

1 Reviews: a) I. Ryu and N. Sonoda, *Angew. Chem., Int. Ed. Engl.*, **35**, 1050 (1996). b) I. Ryu, N. Sonoda, and D. P. Curran, *Chem. Rev.*, **96**, 177 (1996). c) I. Ryu, *Chem. Soc. Rev.*, **30**, 16 (2001). d) I. Ryu, *Chem. Rec.*, **2**, 249 (2002). Also see a review on acyl radicals: e) C. Chatgilialoglu, D. Crich, M. Komatsu, and I. Ryu, *Chem. Rev.*, **99**, 1991 (1999).

2 C. Chatgilialoglu, *Acc. Chem. Res.*, **25**, 188 (1992).

3 I. Ryu, K. Nagahara, A. Kurihara, M. Komatsu, and N. Sonoda, *J. Organomet. Chem.*, **548**, 105 (1997).

4 **2a**: ^{1}H NMR (500 MHz, CDCl$_3$) δ 0.18 (s, 27H), 1.23 (t, J = 7.1 Hz, 3H), 1.39–1.53 (m, 1H), 2.27–2.34 (m, 2H), 2.46–2.49 (m, 1H), 2.62–2.68 (m, 2H), 2.83 (dd, J = 16.5, 4.6 Hz, 1H), 4.10–4.14 (m, 2H), 6.98 (s, 1H); ^{13}C NMR (125 MHz, CDCl$_3$) δ 1.22, 14.19, 26.69, 30.04, 34.76, 45.17, 60.54, 133.03, 151.39, 172.27, 202.52; IR (neat) 1736, 1705, 1620 cm^{-1}; MS (EI) m/z 428 (M$^+$, 9), 413 (39), 356 (100), 281 (90), 73 (100). HRMS (EI) m/z calcd for $C_{19}H_{40}O_3Si_4$ (M$^+$) 428.2054, found 428.2054. **2b**: ^{1}H NMR (500 MHz, CDCl$_3$) δ 0.20 (s, 27H), 1.57–1.62 (m, 1H), 2.39–2.58 (m, 4H), 2.71 (dd, J = 16.3, 7.6 Hz, 1H), 2.84 (dd, J = 17.0, 4.6 Hz, 1H), 7.10 (s, 1H); ^{13}C NMR (125 MHz, CDCl$_3$) δ 1.23, 17.77, 26.21, 29.62, 44.71, 118.07, 136.15, 150.03, 199.65; IR (neat) 2253, 1705, 1620 cm^{-1}; MS (EI) m/z 381 (M$^+$, 12), 366 (24), 308 (100), 73 (77); HRMS (EI) m/z calcd for $C_{17}H_{35}NOSi_4$ (M$^+$) 381.1796, found 381.1789. **3a**: mp 161–162 °C. ^{1}H NMR (500 MHz, CDCl$_3$) δ 0.19 (s, 27H), 0.21 (s, 27H), 1.23–1.27 (m, 6H), 1.39 (s, 3H), 1.51 (s, 1H), 2.23–2.26 (m, 1H), 2.40–2.46 (m, 2H), 2.60–2.66 (m, 2H), 3.08 (d, J = 12.4 Hz, 1H), 4.08–4.19 (m, 2H), 5.46 (s, 1H); ^{13}C NMR (125 MHz, CDCl$_3$) δ 1.45, 2.10, 14.27, 24.07, 25.24, 26.90, 31.94, 35.71, 46.06, 60.50, 86.61, 119.80, 125.14, 160.50, 171.94; IR (neat) 1738 cm^{-1}; MS (EI) m/z 670 (M$^+$ − SiMe$_3$, 100), 242 (44), 73 (86); HRMS (EI) m/z calcd for $C_{29}H_{64}NO_3Si_7$ (M$^+$ − Me$_3$Si) 670.3271, found 670.3274.

5 Preliminary X-ray data for **3a**: $C_{32}H_{73}NO_3Si_8$, fw 744.62, monoclinic, space group $C2/c$ (#15), $a = 41.267(2)$, $b = 9.6886(4)$, $c = 27.994(4)$ Å, $\beta = 119.981$, $V = 9694.8(7)$ Å^3, $T = 296$ K, $Z = 8$, $D_{\mathrm{calcd}} = 1.020$ g/cm^3, $F(000)$ 3264, $R = 0.134$, $R_{\mathrm{W}} = 0.157$ ($I > 5\sigma(I)$) for 10799 observed reflections.

6 The cyclizative silylcarbonylation of 1,5-azaenynes using TTMSS proceeds with smooth chain propagation, see: M. Tojino, N. Otsuka, T. Fukuyama, H. Matsubara, C. H. Schiesser, H. Kuriyama, H. Miyazato, S. Minakata, M. Komatsu, and I. Ryu, *Org. Biomol. Chem.*, **1**, 4262 (2003).

7 a) A. Alberti and C. Chatgilialoglu, *Tetrahedron*, **46**, 3963 (1990). b) M. Ballestri, C. Chatgilialoglu, K. B. Clark, D. Griller, B. Giese, and B. Kopping, *J. Org. Chem.*, **56**, 678 (1991).

8 S. Nakatani, J. Yoshida, and S. Isoe, *J. Chem. Soc., Chem. Commun.*, **1992**, 880.

9 **2c**: ^{1}H NMR (500 Mz, CDCl$_3$) δ 0.88 (t, J = 6.78 Hz, 3H), 1.25 (t, J = 7.33 Hz, 3H), 1.26–1.41 (m, 7H), 1.67 (quint, J = 7.79 Hz, 2H), 2.36–2.46 (m, 3H), 2.50–2.58 (m, 1H), 2.64–2.72 (m, 1H), 2.80–2.88 (m, 3H), 4.14 (q, J = 6.78 Hz, 2H), 7.43 (s, 1H); ^{13}C NMR 125 Mz, CDCl$_3$) δ 14.04, 14.26, 22.54, 26.27, 26.61, 28.16, 30.64, 31.32, 34.79, 34.94, 45.53, 60.62, 131.96, 138.54, 172.38, 202.13; IR (neat) 1730, 1705 cm^{-1}; MS (EI) m/z 298 (M$^+$, 69), 253 (58), 182 (69), 167 (68), 136 (100); HRMS (EI) m/z calcd for $C_{16}H_{26}OS$ (M$^+$) 298.1602, found 298.1603.