

# GaCl<sub>3</sub>-catalyzed $\alpha$ -ethynylation reaction of silyl enol ethers

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## Abstract

GaCl<sub>3</sub> catalyzes  $\alpha$ -ethynylation reaction of silyl enol ethers with triethylsilylated chloroethyne at 130 °C.  
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**Keywords:** Silyl enol ether;  $\alpha$ -Ethynylation; Gallium(III) chloride; Chloroethyne; Catalysis

## 1. Introduction

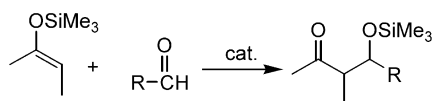
Silyl enol ethers are versatile intermediates in organic synthesis, and are employed in C–C bond formation reactions such as alkylation and aldol reaction (Scheme 1). Since silyl enol ethers themselves are weakly nucleophilic, their reactions are generally conducted in the presence of promoters such as Lewis acids or nucleophilic reagents. The promoters in principle can catalyze such C–C bond formation (Scheme 1), and extensive studies have been conducted for the catalytic aldol addition reaction of silyl enol ethers with acetals or aldehydes (catalytic Mukaiyama aldol reaction) [1]. Only a few catalytic alkylation reactions, however,

have been reported: Chan et al. and Reetz et al. developed ZnBr<sub>2</sub>-catalyzed *tert*-alkylation and benzylation of silyl enol ethers [2]. Paterson et al. reported phenylthiomethylation of silyl enol ethers with  $\alpha$ -chlorosulphides catalyzed by ZnBr<sub>2</sub> [3]. Iqbal et al. conducted phenylthiomethylstannylation of silyl enol ethers with tributyl[(phenylthio)chloromethyl]stannane using the same catalyst [4].

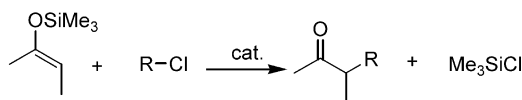
We previously reported one-step  $\alpha$ -ethenylation [5–7] and  $\alpha$ -ethynylation reaction [8,9] of silyl enol ethers with trimethylsilylated acetylene or chloroacetylene in the presence of stoichiometric amounts of GaCl<sub>3</sub>. In case of  $\alpha$ -ethynylation, gallium enolate **2** and chloroethynylgallium **4** formed from silyl enol ether **1** and trimethylsilylchloroethyne **3** underwent carbometallation (carbogallation) giving a digallium intermediate **5** [8].  $\beta$ -Elimination during workup converted **5** to  $\alpha$ -ethynyl ketone **7** via an ethynylgallium **6** (Scheme 2). When the reaction solvent was changed, further carbogallation of **4** and **6** took place giving an  $\alpha$ -ethynylated ketone **8** [9]. Since GaCl<sub>3</sub> was regenerated by the  $\beta$ -elimination of **5**, the  $\alpha$ -ethynylation reaction potentially was catalytic regarding GaCl<sub>3</sub>. The following properties, however, led to the requirement of an excess GaCl<sub>3</sub>: (1) the product **6** of this reaction contained C–Ga bond, and was protodegallated during acid workup; (2)  $\beta$ -elimination of **5** was not always facile, and an appropriate polar solvent was added for the acceleration. It was then considered that catalytic  $\alpha$ -ethynylation could be conducted if carbogallation of **2** took place not with **4** but with **3** itself, and  $\beta$ -elimination of GaCl<sub>3</sub> from **5** could be facilitated. A possible catalytic cycle for the catalytic  $\alpha$ -

### Catalytic reactions of silyl enol ethers

#### aldol reaction



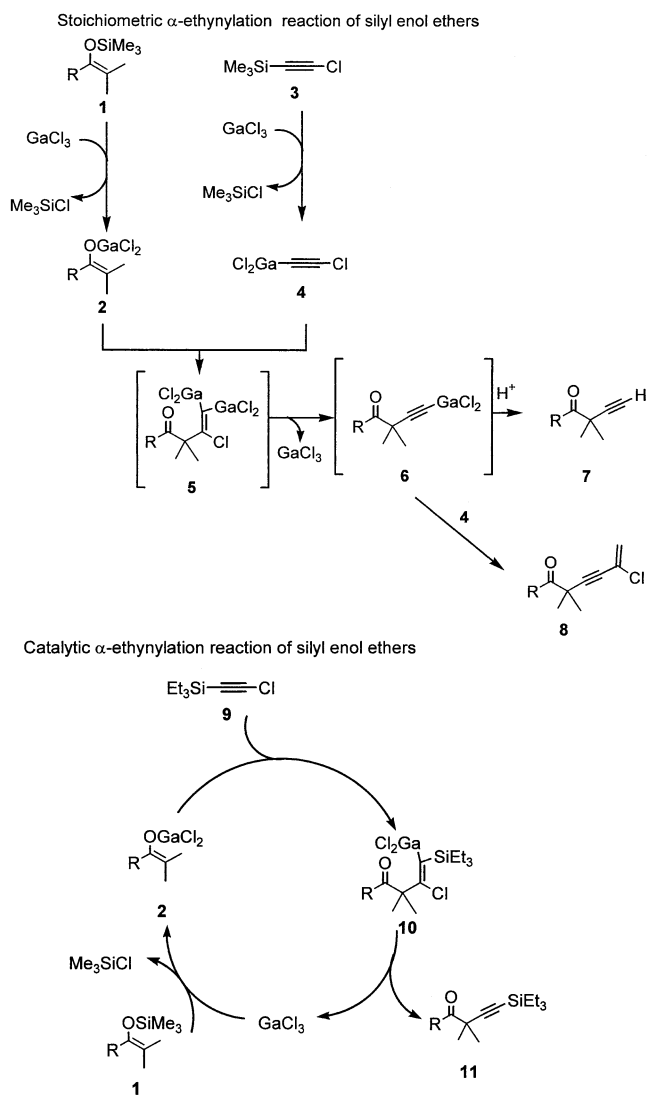
#### alkylation reaction



Scheme 1.

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Scheme 2.

ethynylation is as follows: (i) transmetalation of  $\text{GaCl}_3$  and **1** provides **2**; (ii) carbogallation of **2** and chlorosilyl acetylene **9** gives  $\gamma$ -gallated  $\beta$ -enone **10**; (iii)  $\beta$ -elimination of  $\text{GaCl}_3$  forms  $\alpha$ -silylethynylated ketone **11** and  $\text{GaCl}_3$  (Scheme 2). A related catalytic ethynylation reaction was developed in case of phenol, when triethylsilylated chloroacetylene **9** was reacted at high temperatures [10]. It was, therefore, the subject of the present work whether the methodology could be used in the ethynylation of silyl enol ethers.

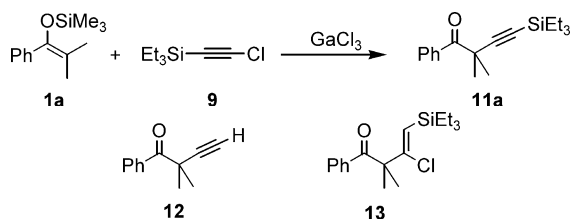
When an equimolar amount of 2-methyl-1-trimethylsilyloxy-1-phenyl-1-propene (**1a**) and chlorotriethylsilyl acetylene **9** in methylcyclohexane (0.25 M) were reacted with  $\text{GaCl}_3$  (400 mol.%) at  $-40^\circ\text{C}$  for 5 min, 2,2-dimethyl-1-phenyl-3-buten-1-one (**12**) was obtained in 39% yield (Table 1, entry 1). The result indicated that the Si–Ga transmetalation took place at low temperature even with the triethylsilyl derivative **9**. When 100 mol.% of  $\text{GaCl}_3$  was used, however, no reaction

occurred at room temperature with quantitative recovery of ketone, which implied that the transmetalation of **1a** generating gallium enolate was more rapid than that of **9** (entry 2). The desired triethylsilylethynyl ketone (**11a**) was obtained in 11% yield by reacting at  $50^\circ\text{C}$ , which could be increased to 49% at refluxing temperature  $130^\circ\text{C}$  (entry 5). Thus, the carbometalation of **9** and gallium enolate **2** does take place without formation of ethynylgallium **4** at the higher temperatures. Since 3-chloro-2,2-dimethyl-1-phenyl-4-triethylsilyl-3-buten-1-one (**13**) was not detected, the  $\beta$ -elimination should be more rapid than the carbogallation under the conditions. It is contrasted to our previous observation that  $\beta$ -elimination is slower than carbogallation of chloroethynylgallium **4** at  $-40^\circ\text{C}$  [8,9].

The catalytic reaction could be conducted by reducing the amount of  $\text{GaCl}_3$  and increasing the concentration of the substrates. An equimolar mixture of **1a** and **9** in methylcyclohexane (2.0 M) was heated at  $130^\circ\text{C}$  with a catalytic amount of  $\text{GaCl}_3$  (10 mol.%) for 4 h to give **11a** in 74% yield with turnover number (TON) 7.4 (entry 7). Use of chlorobenzene that have high boiling point was also effective (entry 9). The yield was even higher under the catalytic conditions compared to the stoichiometric conditions (entries 5 and 7). It may be due to the transmetalation of  $\text{GaCl}_3$  with **9**, which underwent to some extent under the latter conditions. When two equivalents of **1a** were used, the yield of **11a** increased to 83%, TON 8.3 based on **9** (entry 10). Silyl substituent on the chloroacetylene had relatively small effect except for trimethylsilylated **3** (Table 2). The reaction took place even with a triisopropylsilyl derivative **16** (entry 5).

The catalytic reaction could be applied to several silyl enol ethers derived from aromatic and aliphatic ketones **1**, and  $\alpha$ -ethynylated ketones **11** were obtained in high yields. (Table 3). The ethynylation of thermodynamic silyl enol ether formed from 2-methylcyclohexanone (**1h**) took place at the hindered site (entry 8). 2,3-Dimethyl-1-trimethylsilyloxycyclohexanone (**1i**) gave *cis*-2,3-dimethyl derivative **11i** exclusively (entry 9). 2,6-Dimethyl-1-trimethylsilyloxycyclohexanone (**1j**) gave predominantly an isomer *trans*-**11j** with the *trans*-2,6-dimethyl stereochemistry (entry 10), of which was determined by converting to alcohols. The stereochemical outcome was the result of epimerization during the reaction, since treatment of the pure *trans*-**11j** at methylcyclohexane reflux in the presence of 10 mol.%  $\text{GaCl}_3$  for 4 h gave a 5:1 mixture of *trans*-**11j** and *cis*-**11j**. The  $\alpha$ -ethynylation reaction, however, did not take place with silyl enol ethers that are not fully-substituted at the  $\alpha$ -carbon; for example, neither  $\alpha$ -monoethynylated ketone nor its isomerized allene was obtained by the reaction of 6-trimethylsilyloxy-5-undecene, and the ketone was recovered.

Table 1  
 $\alpha$ -Ethynylation of **1a**



Entry	GaCl <sub>3</sub> /mol.%	Solvent (Concentration of <b>9</b> )	Reaction time	Temperature (°C)	Yield <b>11a</b> (%) <sup>a</sup>
1	400	Methylcyclohexane (0.25 M)	5 min	−40	39 <sup>b</sup>
2	100	Methylcyclohexane (0.25 M)	1 h	r.t.	— <sup>c</sup>
3	100	Methylcyclohexane (0.25 M)	1 h	50	11
4	100	Methylcyclohexane (0.25 M)	1 h	100	27
5	100	Methylcyclohexane (0.25 M)	1 h	130	49
6	10	Methylcyclohexane (0.25 M)	4 h	130	24
7	10	Methylcyclohexane (2 M)	4 h	130	74
8	10	CH <sub>2</sub> Cl <sub>2</sub> (2 M)	4 h	40	12
9	10	C <sub>6</sub> H <sub>5</sub> Cl (2 M)	4 h	150	56
10 <sup>d</sup>	10	Methylcyclohexane (2 M)	4 h	130	83

<sup>a</sup> Isolated yield.

<sup>b</sup> The yield of 2,2-dimethyl-1-phenyl-3-butyne-1-one (**12**).

<sup>c</sup> 2-Methyl-1-phenyl-1-propanone was recovered quantitatively.

<sup>d</sup> Two equivalents of **1a** were used.

In summary, silyl enol ethers reacted with triethylsilylchloroethyne in the presence of a catalytic amount of GaCl<sub>3</sub> to give  $\alpha$ -ethynylated ketone.

## 2. Experimental

<sup>1</sup>H-, <sup>13</sup>C-NMR, spectra were recorded on a Varian Mercury NMR (400 MHz) with Me<sub>4</sub>Si as internal standard. IR spectra were measured on JASCO FT/IR-400. Mass spectra were recorded on a JEOL JMS-DX-303 or a JEOL JMS-AX-500.

### 2.1. Synthesis of silyl enol ethers

Silyl enol ethers **1a–1c** were synthesized from 2-methyl-1-arylpropanone by treating with Et<sub>3</sub>N and trimethylsilyl trifluoromethanesulfonates [11]. 2-Methyl-1-trimethylsilyloxycyclohexene (**1h**) and 2,3-dimethyl-1-trimethylsilyloxycyclohexene (**1i**) were prepared according to the literatures [12] [13]. Other silyl enol ethers were synthesized from ketones, LDA, and Me<sub>3</sub>SiCl in THF at −78 °C by a standard method.

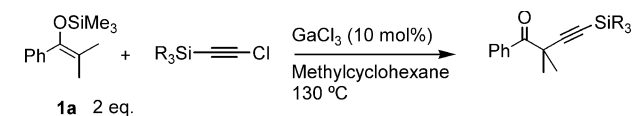
### 2.2. Synthesis of chlorosilylethyne

Chlorosilylethyne **3**, **9**, and **14** were synthesized from *trans*-1,2-dichloroethene, MeLi, and trialkylchlorosilane [14]. In case of chloro(*t*-butyldimethylsilyl)ethyne (**15**) and (triisopropylsilyl)chloroethyne (**16**), *t*-butyldi-

methylsilyl trifluoromethanesulfonate or triisopropylsilyl trifluoromethanesulfonate were used instead of chlorosilane reagents.

### 2.3. 4-Triethylsilyl-2,2-dimethyl-1-phenyl-3-butyne-1-one (**11a**)

Under an argon atmosphere, a solution of GaCl<sub>3</sub> (0.1 ml, 10 mol.%) in methylcyclohexane (1.0 M) was added dropwise to a mixture of 2-methyl-1-trimethylsilyloxy-1-phenyl-1-propene (**1a**) (440 mg, 2.0 mmol) and chlorotriethylsilylethyne (**9**) (174 mg, 1.0 mmol) in methylcyclohexane (0.5 ml) at room temperature (r.t.). The mixture was stirred for 4 h at 130 °C. After cooling to r.t., water was added, and the organic materials were extracted twice with ether. The combined organic layers were washed with brine, and dried over MgSO<sub>4</sub>. The extract was passed through short silica gel column (hexane–ether = 10/1), and concentrated. The residue was purified by flash column chromatography (hexane–EtOAc = 150/1) to give **11a** (283 mg, 83%). <sup>1</sup>H-NMR (400 MHz, CDCl<sub>3</sub>):  $\delta$  0.55 (6H, q, *J* = 8.0 Hz), 0.93 (9H, t, *J* = 7.6 Hz), 1.57 (6H, s), 7.41 (2H, t, *J* = 7.6 Hz), 7.52 (1H, t, *J* = 8.0 Hz), 8.33 (2H, d, *J* = 7.2 Hz). <sup>13</sup>C-NMR (100 MHz, CDCl<sub>3</sub>):  $\delta$  4.5, 7.6, 28.2, 42.6, 86.7, 111.2, 127.7, 129.9, 132.4, 134.9, 198.9. IR (neat): 2955, 2935, 2874, 2152, 1686, 1600, 1384, 1242, 1165, 1019, 724 cm<sup>−1</sup>. MS (EI) *m/z* 286 (M<sup>+</sup>, 29%), 105 (M<sup>+</sup> − C<sub>11</sub>H<sub>21</sub>Si, 100%). HRMS Calc. for C<sub>18</sub>H<sub>26</sub>OSi: 286.1753. Found: 286.1747.

Table 2  
Effect of chlorosilylethyne

Entry	R	Time (h)	Yield (%)
1	CH <sub>3</sub>	3	32
2	C <sub>2</sub> H <sub>5</sub>	9	83
3	<i>n</i> -C <sub>6</sub> H <sub>13</sub>	14	90
4	<i>t</i> -C <sub>4</sub> H <sub>9</sub> (CH <sub>3</sub> ) <sub>2</sub>	15	89
5	<i>i</i> -C <sub>3</sub> H <sub>7</sub>	16	69

#### 2.4. 4-Trimethylsilyl-2,2-dimethyl-1-phenyl-3-butyn-1-one

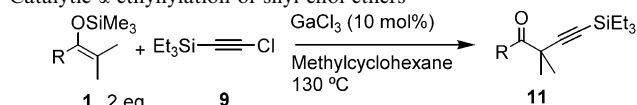
<sup>1</sup>H-NMR (400 MHz, CDCl<sub>3</sub>): δ 0.12 (9H, s), 1.55 (6H, s), 7.41 (2H, t, *J* = 8.0 Hz), 7.51 (1H, t, *J* = 7.6 Hz), 8.28 (2H, d, *J* = 7.6 Hz). <sup>13</sup>C-NMR (100 MHz, CDCl<sub>3</sub>): δ -0.05, 28.0, 42.5, 89.3, 110.1, 127.7, 129.8, 132.3, 134.9, 198.9. IR (neat): 2153, 1687, 1598 843 cm<sup>-1</sup>. MS (EI) *m/z* 244 (M<sup>+</sup>, 40%), 105 (M<sup>+</sup> - C<sub>5</sub>H<sub>9</sub>Si, 100%). HRMS Calc. for C<sub>15</sub>H<sub>20</sub>OSi: 244.1283. Found: 244.1269.

#### 2.5. 4-Trihexylsilyl-2,2-dimethyl-1-phenyl-3-butyn-1-one

<sup>1</sup>H-NMR (400 MHz, CDCl<sub>3</sub>): δ 0.54 (6H, t, *J* = 7.6 Hz), 0.87 (9H, t, *J* = 7.2 Hz), 1.20–1.31 (24H, m), 1.56 (6H s), 7.39 (2H, t, *J* = 6.8 Hz), 7.50 (1H, t, *J* = 7.6 Hz), 8.30 (2H, d, *J* = 8.0 Hz). <sup>13</sup>C-NMR (100 MHz, CDCl<sub>3</sub>): δ 10.3, 11.2, 19.6, 20.8, 25.0, 28.5, 30.1, 39.5, 84.5, 107.8, 124.5, 126.8, 129.2, 131.7, 195.7. IR (neat): 2922, 2152, 1688, 1598, 761 cm<sup>-1</sup>. MS (EI) *m/z* 454 (M<sup>+</sup>, 33%), 370 (M<sup>+</sup> - C<sub>6</sub>H<sub>12</sub>, 100%). HRMS Calc. for C<sub>30</sub>H<sub>50</sub>OSi: 454.3631. Found: 454.3634.

#### 2.6. 4-(*t*-Butyldimethylsilyl)-2,2-dimethyl-1-phenyl-3-butyn-1-one

<sup>1</sup>H-NMR (400 MHz, CDCl<sub>3</sub>): δ 0.55 (6H, t, *J* = 7.2 Hz), 0.85 (9H, t, *J* = 7.2 Hz), 1.26–1.32 (12H, m), 1.55 (3H, s), 1.56 (3H, s), 7.39 (2H, t, *J* = 7.6 Hz), 7.50 (1H, t, *J* = 7.6 Hz), 8.30 (2H, d, *J* = 7.2 Hz). <sup>13</sup>C-NMR (100 MHz, CDCl<sub>3</sub>): δ 13.1, 13.9, 26.2, 26.5, 28.2, 42.6, 87.6, 110.9, 127.7, 129.9, 132.3, 134.9, 198.9. IR (neat): 2924, 2151, 1687, 1598, 714 cm<sup>-1</sup>. MS (EI) *m/z* 370 (M<sup>+</sup>, 31%), 105 (M<sup>+</sup> - C<sub>14</sub>H<sub>27</sub>Si, 100%). HRMS Calc. for C<sub>24</sub>H<sub>38</sub>OSi: 370.2692. Found: 370.2722.

Table 3  
Catalytic α-ethynylation of silyl enol ethers

entry	substrate	product	Time/h	yield/%
1			4	83
2			6	80
3			8	80
4			11	80
5			9	96
6			6	72
7			12	93
8			24	54
9			24	37
10			6	70 <sup>d</sup>
11			4	98
12			25	36

<sup>a</sup>*E/Z* = 1:1. <sup>b</sup>*E/Z* = 1:2. <sup>c</sup>A 9:1 mixture with 2-methyl and 6-methyl-1-trimethylsilyloxy-1-cyclohexene. <sup>d</sup>A mixture of *trans*-**11j**:*cis*-**11j** = 8:1 as determined by <sup>1</sup>H-NMR.

#### 2.7. 4-Triisopropylsilyl-2,2-dimethyl-1-phenyl-3-butyn-1-one

<sup>1</sup>H-NMR (400 MHz, CDCl<sub>3</sub>): δ 1.02 (21H, m), 1.58 (6H, s), 7.39 (2H, t, *J* = 7.2 Hz), 7.50 (1H, t, *J* = 7.2 Hz), 8.33 (2H, d, *J* = 8.0 Hz). <sup>13</sup>C-NMR (100 MHz, CDCl<sub>3</sub>): δ 11.3, 18.7, 28.4, 42.7, 85.6, 111.8, 127.7, 129.9, 132.4, 135.0, 199.0. IR (neat): 2866, 2151, 1689, 1598, 714 cm<sup>-1</sup>. MS (EI) *m/z* 328 (M<sup>+</sup>, 2%), 285 (M<sup>+</sup> - C<sub>3</sub>H<sub>7</sub>, 100%), 105 (M<sup>+</sup> - C<sub>11</sub>H<sub>21</sub>Si, 55%). HRMS Calc. for C<sub>21</sub>H<sub>32</sub>OSi: 328.2222. Found: 328.2212.

#### 2.8. 4-Triethylsilyl-1-(4-fluorophenyl)-2,2-dimethyl-3-butyn-1-one (**11b**)

<sup>1</sup>H-NMR (400 MHz, CDCl<sub>3</sub>): δ 0.54 (6H, q, *J* = 8.0 Hz), 0.92 (9H, t, *J* = 8.0 Hz), 1.54 (6H, s), 7.06 (2H, t, *J* = 8.4 Hz), 8.37 (2H, d, *J* = 9.2 Hz). <sup>13</sup>C-NMR (100 MHz, CDCl<sub>3</sub>): δ 4.5, 7.6, 28.2, 42.5, 87.1, 111.1, 114.7 (d, 21 Hz), 131.0, 132.6 (d, 9.1 Hz), 165.0 (d, 252 Hz),

197.2. IR (neat): 2956, 2913, 2152, 1687, 1600, 727  $\text{cm}^{-1}$ . MS (EI)  $m/z$  304 ( $\text{M}^+$ , 26%), 123 ( $\text{M}^+$  –  $\text{C}_{14}\text{H}_{25}\text{Si}$ , 100%). HRMS Calc. for  $\text{C}_{18}\text{H}_{25}\text{FOSi}$ : 304.1659. Found: 304.1662.

2.9. 4-Triethylsilyl-1-(4-methoxyphenyl)-2,2-dimethyl-3-butyn-1-one (**11c**)

$^1\text{H-NMR}$  (400 MHz,  $\text{CDCl}_3$ ):  $\delta$  0.56 (6H, q,  $J = 8.0$  Hz), 0.94 (9H, t,  $J = 8.0$  Hz), 1.56 (6H, s), 3.87 (3H, s), 6.88 (2H, t,  $J = 8.0$  Hz), 8.36 (2H, d,  $J = 8.0$  Hz).  $^{13}\text{C-NMR}$  (100 MHz,  $\text{CDCl}_3$ ):  $\delta$  4.5, 7.6, 28.4, 42.3, 55.4, 86.4, 111.7, 112.8, 127.5, 132.3, 162.8, 197.1. IR (neat): 2955, 2150, 1677, 1602, 726  $\text{cm}^{-1}$ . MS (EI)  $m/z$  316 ( $\text{M}^+$ , 12%), 135 ( $\text{M}^+$  –  $\text{C}_{14}\text{H}_{25}\text{Si}$ , 100%). HRMS Calc. for  $\text{C}_{19}\text{H}_{28}\text{O}_2\text{Si}$ : 316.1859. Found: 316.1855.

2.10. 4-Triethylsilyl-2-butyl-2-methyl-1-phenyl-3-butyn-1-one (**11d**)

$^1\text{H-NMR}$  (400 MHz,  $\text{CDCl}_3$ ):  $\delta$  0.56 (6H, q,  $J = 8.0$  Hz), 0.87 (3H, t,  $J = 8.0$  Hz), 0.92–1.00 (12H, m), 1.26–1.40 (4H, m), 1.72–1.82 (2H, m), 1.98–2.08 (2H, m), 7.38 (2H, t,  $J = 7.6$  Hz), 7.49 (1H, t,  $J = 7.6$  Hz), 8.21 (2H, d,  $J = 8.0$  Hz).  $^{13}\text{C-NMR}$  (100 MHz,  $\text{CDCl}_3$ ):  $\delta$  4.6, 7.6, 9.6, 14.1, 23.1, 27.2, 31.9, 38.3, 52.7, 89.1, 109.6, 127.5, 129.3, 131.9, 136.9, 200.4. IR (neat): 2874, 2159, 1683, 1598, 1227  $\text{cm}^{-1}$ . MS (EI)  $m/z$  342 ( $\text{M}^+$ , 35%), 105 ( $\text{M}^+$  –  $\text{C}_{15}\text{H}_{29}\text{Si}$ , 100%). HRMS Calc. for  $\text{C}_{22}\text{H}_{34}\text{OSi}$ : 342.2379. Found: 342.2372.

2.11. 4-Triethylsilyl-2-methyl-1,2-diphenyl-3-butyn-1-one (**11e**)

$^1\text{H-NMR}$  (400 MHz,  $\text{CDCl}_3$ ):  $\delta$  0.5 (6H, q,  $J = 8.4$  Hz), 0.90 (9H, t,  $J = 8.0$  Hz), 1.77 (3H, s), 7.21–7.26 (3H, m), 7.31–7.38 (3H, m), 7.52 (2H, d,  $J = 7.2$  Hz), 7.91 (2H, d,  $J = 7.2$  Hz).  $^{13}\text{C-NMR}$  (100 MHz,  $\text{CDCl}_3$ ):  $\delta$  4.5, 7.5, 30.4, 52.5, 91.4, 108.0, 125.7, 127.1, 127.4, 128.8, 130.5, 132.1, 134.4, 141.9, 195.7. IR (neat): 2955, 2165, 1690, 1598, 1579, 1230, 730  $\text{cm}^{-1}$ . MS (EI)  $m/z$  348 ( $\text{M}^+$ , 69%), 105 ( $\text{M}^+$  –  $\text{C}_{17}\text{H}_{23}\text{Si}$ , 100%). HRMS Calc. for  $\text{C}_{23}\text{H}_{28}\text{OSi}$ : 348.1909. Found: 348.1913.

2.12. Phenyl [1-(triethylsilylethynyl)cyclohexyl] ketone (**11f**)

$^1\text{H-NMR}$  (400 MHz,  $\text{CDCl}_3$ ):  $\delta$  0.58 (6H, q,  $J = 7.6$  Hz), 0.96 (9H, t,  $J = 7.6$  Hz), 1.18–1.28 (1H, m), 1.62–1.70 (4H, m), 1.70–1.72 (1H, m), 1.78–1.90 (2H, m), 2.45–2.25 (2H, m), 7.39 (2H, t,  $J = 8.0$  Hz), 7.50 (1H, t,  $J = 7.6$  Hz), 8.28 (2H, d,  $J = 8.0$  Hz).  $^{13}\text{C-NMR}$  (100 MHz,  $\text{CDCl}_3$ ):  $\delta$  4.6, 7.7, 22.5, 25.7, 26.0, 29.5, 35.6, 48.6, 89.9, 108.6, 127.6, 128.1, 128.4, 129.7, 132.1, 135.5, 199.4. IR (neat): 2933, 2874, 2152, 1684, 1598, 1238, 743  $\text{cm}^{-1}$ . MS (EI)  $m/z$  326 ( $\text{M}^+$ , 19%), 105 ( $\text{M}^+$  –

$\text{C}_{14}\text{H}_{25}\text{Si}$ , 100%). HRMS Calc. for  $\text{C}_{21}\text{H}_{30}\text{OSi}$ : 326.2066. Found: 326.2062.

2.13. Cyclohexyl [1-(triethylsilylethynyl)cyclohexyl] ketone (**11g**)

$^1\text{H-NMR}$  (400 MHz,  $\text{CDCl}_3$ ):  $\delta$  0.60 (6H, q,  $J = 8.0$  Hz), 1.01 (9H, t,  $J = 8.0$  Hz), 1.10–1.42 (6H, m), 1.47–1.56 (2H, m), 1.60–1.70 (6H, m), 1.72–1.84 (6H, m), 3.12 (1H, t,  $J = 11.2$  Hz).  $^{13}\text{C-NMR}$  (100 MHz,  $\text{CDCl}_3$ ):  $\delta$  4.7, 7.7, 22.4, 25.5, 25.8, 25.9, 30.2, 33.8, 47.1, 51.0, 87.5, 108.2, 212.6. IR (neat): 2932, 2874, 2856, 2153, 1712, 1449, 740  $\text{cm}^{-1}$ . MS (EI)  $m/z$  332 ( $\text{M}^+$ , 71%), 83 ( $\text{M}^+$  –  $\text{C}_{15}\text{H}_{26}\text{OSi}$ , 100%). HRMS Calc. for  $\text{C}_{21}\text{H}_{36}\text{OSi}$ : 332.2535. Found: 332.2522.

2.14. 2-Triethylsilylethynyl-2-methylcyclohexanone (**11h**)

$^1\text{H-NMR}$  (400 MHz,  $\text{C}_6\text{D}_6$ ):  $\delta$  0.57 (6H, q,  $J = 8.0$  Hz), 1.03 (9H, t,  $J = 8.0$  Hz), 1.02–1.37 (3H, m), 1.42 (3H, s), 1.58–1.65 (1H, m), 1.87 (1H, ddd,  $J = 13.2, 6.0, 3.2$  Hz), 2.04 (1H, dddd,  $J = 13.6, 13.2, 3.6, 3.6$  Hz), 2.18–2.24 (1H, m), 3.00 (1H, ddd,  $J = 13.2, 6.0, 6.0$  Hz).  $^{13}\text{C-NMR}$  (100 MHz,  $\text{CDCl}_3$ ):  $\delta$  4.6, 7.6, 22.6, 23.4, 28.3, 38.6, 42.3, 46.9, 86.2, 109.5, 208.6. IR (neat): 2935, 2165, 1725, 726  $\text{cm}^{-1}$ . MS (EI)  $m/z$  250 ( $\text{M}^+$ , 2.4%), 221 ( $\text{M}^+$  –  $\text{C}_2\text{H}_5$ , 100%). HRMS Calc. for  $\text{C}_{15}\text{H}_{26}\text{OSi}$ : 250.1753. Found: 250.1746.

2.15. *cis*-2,3-Dimethyl-2-(triethylsilylethynyl)cyclohexanone (**11i**)

$^1\text{H-NMR}$  (400 MHz,  $\text{C}_6\text{D}_6$ ):  $\delta$  0.60 (6H, q,  $J = 8.0$  Hz), 0.64 (3H, d,  $J = 7.2$  Hz), 1.07 (9H, t,  $J = 8.0$  Hz), 1.33 (3H, s), 1.43–1.50 (2H, m), 2.04–2.10 (1H, m), 2.14 (1H, ddd,  $J = 13.6, 4.8, 4.8$  Hz), 2.26–2.35 (2H, m), 2.93 (1H, ddd,  $J = 13.2, 11.6, 6.8$  Hz).  $^{13}\text{C-NMR}$  (100 MHz,  $\text{CDCl}_3$ ):  $\delta$  4.6, 7.7, 14.4, 20.5, 23.1, 29.3, 38.1, 43.2, 50.5, 85.7, 110.7, 209.2. IR (neat): 2955, 2167, 1723, 730  $\text{cm}^{-1}$ . MS (EI)  $m/z$  264 ( $\text{M}^+$ , 1.5%), 43 ( $\text{M}^+$  –  $\text{C}_{13}\text{H}_{21}\text{O}$ , 100%). HRMS Calc. for  $\text{C}_{16}\text{H}_{28}\text{OSi}$ : 264.1909. Found: 264.1920. NOE between the 2-methyl protons and 3-methyl protons showed the *cis* configuration of 2-methyl group and 3-methyl group.

2.16. *trans*-2,6-Dimethyl-2-(triethylsilylethynyl)cyclohexanone (**11j**)

The ratio of *trans*:*cis* = 8:1 was determined by  $^1\text{H-NMR}$ , and pure *trans*-**11j** and *cis*-**11j** were isolated by flash column chromatography.  $^1\text{H-NMR}$  (400 MHz,  $\text{C}_6\text{D}_6$ ):  $\delta$  0.58 (6H, q,  $J = 8.0$  Hz), 0.97–1.20 (5H, m), 1.04 (9H, t,  $J = 8.0$  Hz), 1.32–1.37 (1H, m), 1.45 (3H, s), 1.69–1.75 (1H, m), 1.91 (1H, ddd,  $J = 13.2, 6.0, 3.2$  Hz), 2.18 (1H, dddd,  $J = 26.8, 13.6, 3.6, 3.6$  Hz), 3.27 (1H,

ddq,  $J = 12.8, 6.4, 6.4$  Hz).  $^{13}\text{C-NMR}$  (100 MHz,  $\text{CDCl}_3$ ):  $\delta$  4.6, 7.6, 14.9, 22.7, 23.5, 37.4, 41.3, 43.0, 47.0, 85.8, 110.1, 210.2. IR (neat): 2934, 2161, 1722, 746  $\text{cm}^{-1}$ . MS (EI)  $m/z$  264 ( $\text{M}^+$ , 7%), 235 ( $\text{M}^+ - \text{C}_2\text{H}_5$ , 100%). HRMS Calc. for  $\text{C}_{16}\text{H}_{28}\text{OSi}$ : 264.1909. Found: 264.1878.

2.17. *cis*-2,6-Dimethyl-2-(triethylsilylethynyl)cyclohexanone *cis* (**11j**)

$^1\text{H-NMR}$  (400 MHz,  $\text{CDCl}_3$ ):  $\delta$  0.59 (6H, q,  $J = 7.6$  Hz), 0.99 (9H, t,  $J = 7.6$  Hz), 1.10 (3H, d,  $J = 6.4$  Hz), 1.51–1.65 (2H, m), 1.88–1.92 (1H, m), 1.98–2.05 (1H, m), 2.22–2.26 (1H, m), 3.07 (1H, dq,  $J = 10.0, 6.4$  Hz).  $^{13}\text{C-NMR}$  (100 MHz,  $\text{CDCl}_3$ ):  $\delta$  4.7, 7.7, 16.8, 20.6, 26.6, 29.8, 31.1, 38.0, 44.7, 51.8, 87.6, 107.2, 208.9. IR (neat): 2934, 2161, 1722, 746  $\text{cm}^{-1}$ . MS (EI)  $m/z$  264 ( $\text{M}^+$ , 8%), 235 ( $\text{M}^+ - \text{C}_2\text{H}_5$ , 100%). HRMS Calc. for  $\text{C}_{16}\text{H}_{28}\text{OSi}$ : 264.1909. Found: 264.1910.

2.18. *trans*-2,6-Dimethyl-2-(triethylsilylethynyl)cyclohexanol (equatorial)

Under an argon atmosphere, to lithium aluminum hydride (13 mg, 0.33 mmol) in ether (2 ml) was added *trans*-**11j** (45.9 mg, 0.17 mmol) in ether (2 ml) at 0 °C. The mixture was stirred at r.t. for 10 min, and hydrolyzed by adding 6 M  $\text{H}_2\text{SO}_4$ . The organic materials were extracted twice with ether. The combined organic layers were washed with brine, dried over  $\text{MgSO}_4$ , and concentrated. The residue was purified by flash column chromatography to give *trans*-2,6-dimethyl-2-(triethylsilylethynyl)cyclohexanol (equatorial) (26.9 mg, 59%) and *trans*-2,6-dimethyl-2-(triethylsilylethynyl)cyclohexanol (axial) (16.5 mg, 35%).  $^1\text{H-NMR}$  (400 MHz,  $\text{CDCl}_3$ ):  $\delta$  0.58 (6H, q,  $J = 8.0$  Hz), 0.99 (9H, t,  $J = 8.0$  Hz), 1.02 (3H, d,  $J = 6.8$  Hz), 1.21 (1H, ddd,  $J = 13.2, 13.2, 3.6$  Hz), 1.31 (3H, s), 1.36 (1H, d,  $J = 11.6$  Hz), 1.46–1.52 (2H, m), 1.57–1.72 (3H, m), 1.81–1.86 (1H, m), 2.66 (1H, dd,  $J = 11.2, 10.0$  Hz).  $^{13}\text{C-NMR}$  (100 MHz,  $\text{CDCl}_3$ ):  $\delta$  4.8, 7.8, 18.9, 22.6, 27.5, 34.2, 37.4, 39.1, 41.3, 81.8, 85.7, 110.4. IR (neat): 3488 (br), 2874, 2161, 736  $\text{cm}^{-1}$ . MS (EI)  $m/z$  266 ( $\text{M}^+$ , 5%), 237 ( $\text{M}^+ - \text{C}_2\text{H}_5$ , 44%), 103 ( $\text{M}^+ - \text{C}_8\text{H}_{23}\text{OSi}$ , 100%). HRMS Calc. for  $\text{C}_{16}\text{H}_{30}\text{OSi}$ : 266.2066. Found: 266.2037. NOE between the 2-methyl protons and the 6-proton showed the axial arrangement of the 2-methyl group.

2.19. *trans*-2,6-Dimethyl-2-(triethylsilylethynyl)cyclohexanol (axial)

$^1\text{H-NMR}$  (400 MHz,  $\text{CDCl}_3$ ):  $\delta$  0.56 (6H, q,  $J = 8.0$  Hz), 0.95 (3H, d,  $J = 6.4$  Hz), 0.98 (9H, t,  $J = 8.0$  Hz), 1.10–1.20 (1H, m), 1.25 (3H, s), 1.30–1.40 (2H, m), 1.43–1.47 (2H, m), 1.50–1.57 (1H, m), 1.66–1.75 (1H,

m), 2.66–2.22 (1H, m), 3.44 (1H, d,  $J = 4.8$  Hz).  $^{13}\text{C-NMR}$  (100 MHz,  $\text{CDCl}_3$ ):  $\delta$  4.8, 7.7, 18.9, 22.8, 26.6, 27.1, 32.1, 33.0, 38.5, 77.1, 83.7, 113.8. IR (neat): 3467 (br), 2877, 2162, 726  $\text{cm}^{-1}$ . MS (EI)  $m/z$  266 ( $\text{M}^+$ , 5%), 237 ( $\text{M}^+ - \text{C}_2\text{H}_5$ , 96%), 103 ( $\text{M}^+ - \text{C}_8\text{H}_{23}\text{OSi}$ ). HRMS Calc. for  $\text{C}_{16}\text{H}_{30}\text{OSi}$ : 266.2066. Found: 266.2088.

2.20. 6-Triethylsilyl-2,4,4-trimethyl-5-hexyn-3-one (**11k**)

$^1\text{H-NMR}$  (400 MHz,  $\text{CDCl}_3$ ):  $\delta$  0.58 (6H, q,  $J = 7.6$  Hz), 0.99 (9H, t,  $J = 7.6$  Hz), 1.12 (3H, s), 1.14 (3H, s), 1.35 (6H, s).  $^{13}\text{C-NMR}$  (100 MHz,  $\text{CDCl}_3$ ):  $\delta$  4.6, 7.6, 20.4, 26.4, 36.4, 44.6, 84.6, 110.5, 213.8. IR (neat): 2875, 2155, 1720, 728  $\text{cm}^{-1}$ . MS (EI)  $m/z$  252 ( $\text{M}^+$ , 19%), 43 ( $\text{M}^+ - \text{C}_{12}\text{H}_{21}\text{OSi}$ , 100%). HRMS Calc. for  $\text{C}_{15}\text{H}_{28}\text{OSi}$ : 252.1909. Found: 252.1902.

2.21. 5,7-Dibutyl-5-triethylsilylethynyl-6-undecanone (**11l**)

$^1\text{H-NMR}$  (400 MHz,  $\text{CDCl}_3$ ):  $\delta$  0.61 (6H, q,  $J = 7.6$  Hz), 0.88 (12H, t,  $J = 6.8$  Hz), 1.01 (9H, t,  $J = 7.6$  Hz), 1.18–1.50 (20H, m), 1.60–1.78 (4H, m), 3.18 (1H, quintet,  $J = 6.4$  Hz).  $^{13}\text{C-NMR}$  (100 MHz,  $\text{CDCl}_3$ ):  $\delta$  4.7, 7.7, 14.1, 23.0, 23.1, 23.1, 27.3, 29.6, 29.7, 30.4, 30.8, 37.7, 48.6, 51.1, 54.0, 87.1, 109.1, 212.8. IR (neat): 2956, 2160, 1711, 725  $\text{cm}^{-1}$ . MS (EI)  $m/z$  420 ( $\text{M}^+$ , 56%), 377 ( $\text{M}^+ - \text{C}_3\text{H}_7$ , 100%). HRMS Calc. for  $\text{C}_{27}\text{H}_{52}\text{OSi}$ : 420.3787. Found: 420.3788.

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