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Bismuth(III) chloride-catalyzed direct deoxygenative allylation of substituted benzylic alcohols with allyltrimethylsilane

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Abstract—A highly effective protocol for allylation of *sec*-benzyl alcohols with allyltrimethylsilane in the presence of a catalytic amount of bismuth(III) chloride has been developed.

1. Introduction

The Lewis acid mediated nucleophilic allylation of carbonyl compounds[1] and acetals[2] has been extensively investigated and well documented. However, the direct substitution of the hydroxyl group in alcohols by nucleophiles is far less developed. Generally, this transformation requires an equimolar or excess amount of acid because of the poor leaving ability of the hydroxyl group. As a result, hydroxyl groups are transformed into the corresponding halides,[3] acetates,[4] or other good leaving groups before treatment with the nucleophile. In the literature there is quite a plethora of procedures reported for allylation of alcohols employing $BF_3{\cdot}OEt_2$,[5] $B(C_6F_5)_3$,[4] bis(fluorosulfuryl)imide,[6] $InCl_3$,[7] and $InBr_3$[8] as catalysts or as stoichiometric reagents. However, many of these methods have some drawbacks such as low yields of the products,[5] long reaction times, harsh reaction conditions,[4,5] difficulties in work up, use of stoichiometric[5] and/or relatively expensive reagents,[7,8] the requirement for an inert atmosphere,[4–6] and formation of a significant amount of side products.[5] In this context, direct allylation of alcohols in a catalytic manner under nearly neutral conditions could be an elegant and useful procedure in synthetic organic chemistry.[9] In continuation of our work to development of new synthetic organic transformations,[10] herein, we wish to report a very simple method for the allylation of alcohols with allylsilane in the presence of a catalytic amount of bismuth(III) chloride.

2. Results and discussion

Bismuth(III) halides are inexpensive, relatively nontoxic, fairly water insensitive, and environmentally benign reagents, which have been used as mild Lewis acid catalysts for an array of synthetic transformations.[11,12] Bismuth has an electron configuration of $[Xe]4f^{14}5d^{10}6s^26p^3$. Due to the weak shielding of the 4f electrons (lanthanide contraction), bismuth(III) compounds exhibit Lewis acidity. Preliminary studies demonstrated that the nature of bismuth(III) halides was inconsequential in terms of efficiency and selectivity (Cl ~ Br ~ I). However, bismuth(III) triflate is not a satisfactory catalyst for this reaction. In a search for suitable allyl sources (Table 1), it was found that allylmagnesium chloride or allyltributyltin, which are highly nucleophilic, are not suitable for these conditions and only starting alcohols are recovered. The unique catalytic activity of bismuth(III) chloride and a silyl

Table 1. $BiCl_3$-catalyzed allylation of benzhydrol from different allyl-sources[a]

Entry	Nucleophile	Time (h)	Yield (%)
1	Allyltrimethylsilane	1	92
2	Allyltributyltin	6	0
3	Allylmagnesium chloride	6	0

[a] 1 mmol benzhydrol, 1.5 mmol allyltrimethylsilane, 5 mol % $BiCl_3$, dichloromethane (0.2 M) were used.

Keywords: Bismuth(III) chloride; Alcohols; Allyltrimethylsilane; Allylation.
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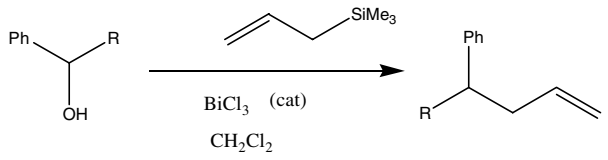


Scheme 1.

nucleophile are the best combination for the success of the allylation reaction (Scheme 1). We have examined other Lewis acids for this reaction (Table 3) but catalytically these are inefficient; perhaps due to the instability of these catalysts under protic conditions. Bismuth(III) chloride is the best catalyst for allylation of alcohols with silyl nucleophiles;[13] with benzhydrols, as low as 1 mol % catalyst is sufficient to obtain the desired products. It should be mentioned that bismuth(III) chloride-catalyzed allylation reactions are faster in dichloromethane than other solvents examined including tetrahydrofuran, hexane, benzene, and *N*,*N*-dimethylformamide (Table 2). The bismuth(III) chloride-catalyzed allylation of alcohols is not affected by solvent concentration: 0.5, 0.2, 0.1 M all gave almost the same yields, entries 1–3 in Table 2. The reaction of benzhydrol or its derivatives, which have electron-donating or withdrawing groups on the aryl rings with silyl nucleophile in the presence of 1 mol % $BiCl_3$ at room temperature, afforded the desired alkenes in 1 h smoothly without any side products[13] in 84–95% yield.

Table 2. Solvent effects on $BiCl_3$-catalyzed allylation of benzhydrol with allyltrimethylsilane at room temperature[a]

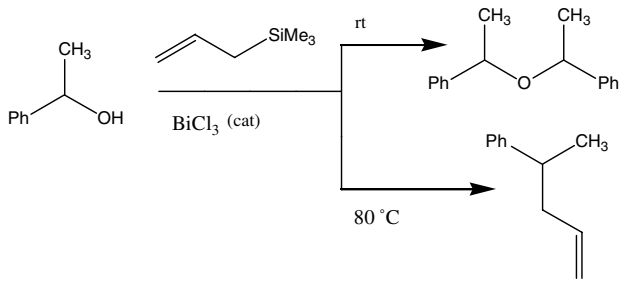
Entry	Solvent	Time (min)	Yield (%)
1	CH_2Cl_2 (0.5 M)	30	92
2	CH_2Cl_2 (0.2 M)	30	91
3	CH_2Cl_2 (0.1 M)	30	86
4	THF	30	15
5	CH_3CN	30	73
6	Hexane	30	15
7	DMF	30	10
8	Benzene	30	10

[a] 1 mmol benzhydrol, 1.5 mmol allyltrimethylsilane, 5 mol % $BiCl_3$, solvent (0.2 M) were used.

Table 3. Reaction of benzhydrol with allyltrimethylsilane at room temperature[a]

Entry	Catalyst (mol %)	Time	Yield (%)
1	None	24 h	0
2	$BiCl_3$ (5)	30 min	92
3	$BiCl_3$ (2.5)	90 min	89
4	$BiCl_3$ (1)	360 min	77
5	$RuCl_3$ (5)	20 min	15
6	$AlCl_3$ (5)	30 min	36
7	$ScCl_3$ (5)	30 min	23
8	$Sc(OTf)_3$ (5)	30 min	19
9	$Bi(OTf)_3$ (5)	30 min	10
10	$BF_3{\cdot}OEt_2$ (5)	30 min	20
11	$FeCl_3$ (5)	30 min	5
12	$LuCl_3$ (5)	30 min	4

[a] 1 mmol benzhydrol, 1.5 mmol allyltrimethylsilane, and dichloromethane (0.5 M) were used.



Scheme 2.

Interestingly, 1-phenylethanol (entry 1, Table 5) did not give any allylation product with allylsilane at room temperatures. Instead the desired product phenylethanol underwent intermolecular nucleophilic reaction to produce 1-[1-(1-phenylethoxy)ethyl]benzene (Scheme 2). The intermolecular nucleophilic attack was favored over allylation, perhaps due to less bulkiness than the benzhydrols. However, at 80 °C 1-phenylethanol was allylated with allylsilane smoothly affording a high yield of the allylated product without any side products. Similarly, other phenylethanols or sterically bulky secondary and tertiary benzyl alcohols underwent the allylation reaction under the same conditions to give the corresponding allylated products in excellent yields (81–91%).

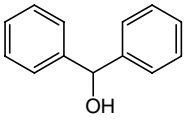
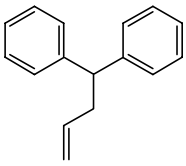
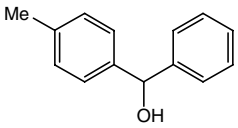
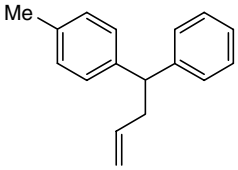
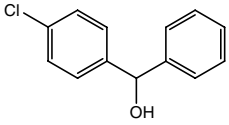
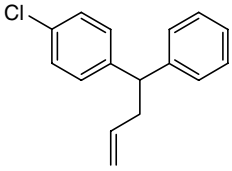
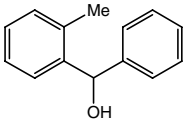
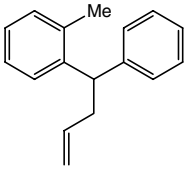
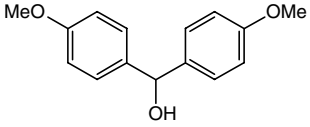
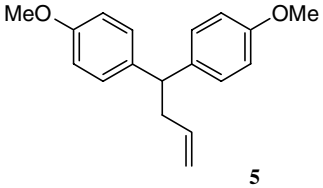
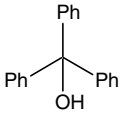
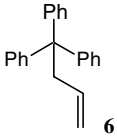
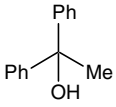
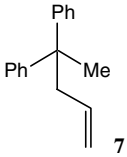
To explore the generality and scope of this reaction further, the $BiCl_3$-catalyzed allylation of alcohols was examined using other functionally and sterically diverse alcohols as depicted in Tables 4 and 5. When trityl alcohol (entry 6, Table 4) was subjected to this method, allylation took place smoothly in excellent yield. Similarly, sterically hindered substrates (entry 7 in Table 4 and entry 3 in Table 5) were allylated in high yield. The simple benzyl alcohol gave only 20% of the desired product[14] and aliphatic alcohols (*tert*-BuOH, 2-hexanol) were not suitable for this system. The method was also extended to other silyl nucleophiles[15] (Scheme 3).

A possible mechanism for this reaction is shown in Scheme 4. Bismuth(III) chloride is a mild Lewis acid that activates the hydroxyl group to generate a carbocation, which is trapped by allylsilane to give the more stable silicon stabilized carbocation. Finally, the TMS group is lost to give the desired product with trimethylsilyl alcohol as a byproduct.

3. Conclusion

In conclusion, we have demonstrated the direct substitution of hydroxyl groups in *sec*-benzylic alcohols by nucleophiles such as allyl-, and alkynylsilanes in the presence of a catalytic amount of $BiCl_3$. In most cases, the reaction requires low catalyst loadings, short reaction times, and proceeds under a non-inert atmosphere. The high yield of products, mildness of the reaction conditions, ease of operation, and use of inexpensive bismuth chloride should make this procedure a valuable tool for the formation of carbon–carbon bonds. Studies

Table 4. $BiCl_3$-catalyzed allylation of benzhydrols with allyltrimethylsilane at room temperature[a]

Entry	Alcohol	Time (h)	Product	Yield (%)
1		0.5	 **1**	92
2		1	 **2**	90
3		1	 **3**	93
4		1	 **4**	92
5		1	 **5**	95
6		3	 **6**	86
7		3	 **7**	84

[a] Reaction conditions: Alcohol (1 mmol), allyltrimethylsilane (1.5 mmol), bismuth(III) chloride (5 mol %), dichloromethane (2 mL) at room temperature.

extending the range of Bi(III)-catalyzed C–C bond forming reactions and the details of the mechanism are currently underway in our laboratory.

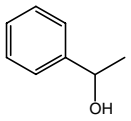
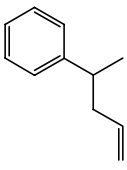
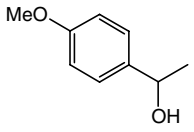
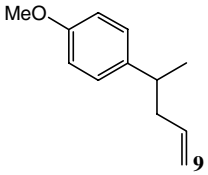
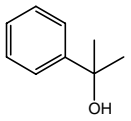
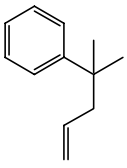
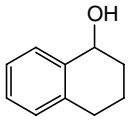
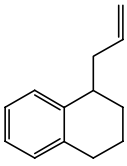
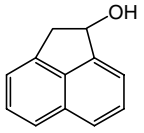
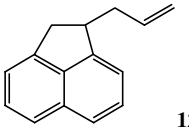
4. Experimental

NMR spectra were recorded on a Bruker ARX 300 (300 MHz) instrument. Low resolution mass spectra (CI, EI) were recorded on a Finnigan 4000 mass spectrometer. High resolution mass spectra (HRMS, EI, CI, ESI) were recorded on Finnigan MAT XL95 mass spectrometer. The reactions were monitored by TLC, and visualized with UV light followed by development using 15% phosphomolybdic acid in ethanol. All solvents and reagents were purchased from Aldrich with high grade quality and used without any purification.

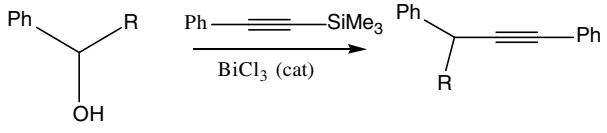
4.1. General procedure for allylation of alcohols

To a stirred solution of benzhydrol (182 mg, 1 mmol) and allyltrimethylsilane (171 mg, 1.5 mmol) in dichloromethane (2 mL) was added $BiCl_3$ (16 mg, 5 mol %) at room temperature. The reaction mixture was stirred at room temperature and the reaction course was monitored by thin layer chromatography. After reaction

Table 5. $BiCl_3$-catalyzed allylation of *sec*-benzyl alcohols with allyltrimethylsilane at 80 °C[a]

Entry	Alcohol	Time (h)	Product	Yield (%)
1		2	 **8**	88
2		3	 **9**	91
3		2	 **10**	89
4		2	 **11**	81
5		3	 **12**	82

[a] Reaction conditions: Alcohol (1 mmol), allyltrimethylsilane (2 mmol), bismuth(III) chloride (5 mol %), 1,2-dichloroethane (5 mL) at 80 °C.



13: R = Me, 92%; **14**: R = Ph, 95%.

Scheme 3.

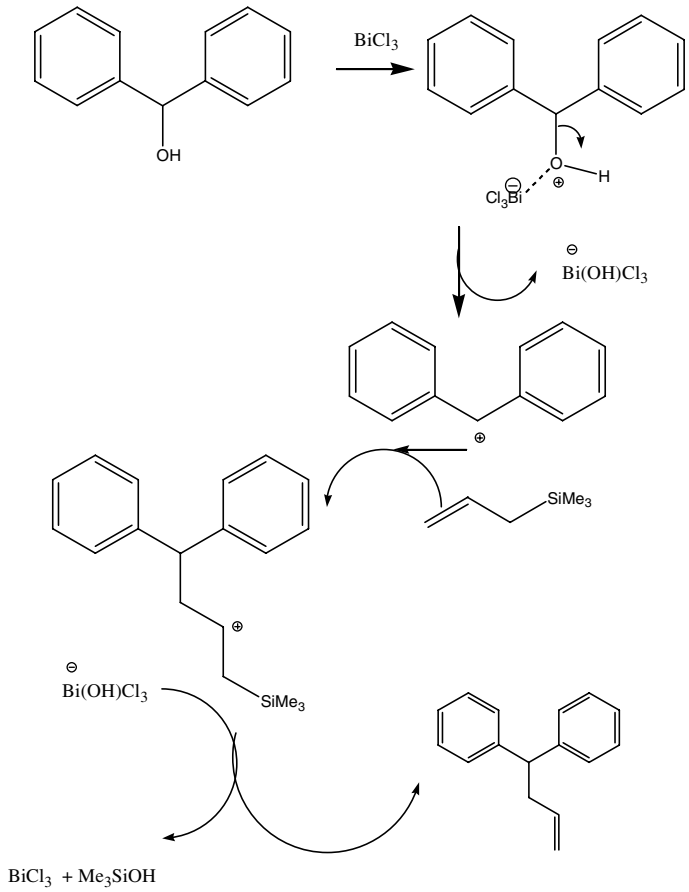
was complete (30 min), the solvent was removed in vacuo, and the residue was chromatographed over silica gel (1% ethyl acetate in hexane) to give a pure product.

4.1.1. 4,4-Diphenyl-1-butene (1). ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.35–7.17 (m, 10H), 5.84–5.70 (m, 1H), 5.11–4.98 (m, 2H), 4.06 (t, $J = 7.8$ Hz, 1H), 2.87 (t, $J = 7.2$ Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 144.5, 136.8, 128.4, 127.9, 126.2, 116.3, 51.2, 39.9; MS *m*/*z* 208 (M^+); HRMS calcd for $C_{16}H_{16}$ 208.1252, found 208.1250.

4.1.2. 4-(4-Methylphenyl)-4-phenyl-1-butene (2). ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.31–7.04 (m, 9H), 5.79–5.62 (m, 1H), 5.01–4.87 (m, 2H), 4.15 (t, $J = 7.5$ Hz, 1H), 2.75–2.71 (m, 2H); MS *m*/*z* 222 (M^+); HRMS calcd for $C_{17}H_{18}$ 222.1409, found 222.1407.

4.1.3. 4-(4-Chlorophenyl)-4-phenyl-1-butene (3). ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.30–7.01 (m, 9H), 5.68–5.54 (m, 1H), 4.98–4.86 (m, 2H), 3.90 (t, $J = 7.2$ Hz, 1H), 2.72–2.65 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 144.0, 142.9, 136.4, 131.8, 129.3, 128.5, 127.8, 126.4, 116.6, 50.5, 39.8; MS *m*/*z* 244, 242 (M^+); HRMS calcd for $C_{16}H_{15}{}^{35}Cl$ 242.0862, found 242.0859.

4.1.4. 4-(2-Methylphenyl)-4-phenyl-1-butene (4). ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.30–7.05 (m, 9H), 5.78–5.64 (m, 1H), 5.01–4.89 (m, 2H), 4.16 (t, $J = 7.5$ Hz, 1H), 2.77–2.72 (m, 2H), 2.21 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 144.1, 142.2, 137.0, 136.3, 130.1,



Scheme 4.

128.2, 126.8, 126.0, 116.2, 47.0, 40.3, 19.8; MS *m/z* 222 (M^+); HRMS calcd for $C_{17}H_{18}$ 222.1409, found 222.1412.

4.1.5. 4-(4-Methoxyphenyl)-4-(4-methoxyphenyl)-1-butane (5). ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.39 (d, $J = 7.8$ Hz, 4H), 7.06 (d, $J = 7.8$ Hz, 4H), 6.08–5.92 (m, 1H), 5.35–5.16 (m, 2H), 4.18 (t, $J = 7.8$ Hz, 1H), 3.97 (s, 6H), 3.01 (t, $J = 6.9$ Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 157.7, 136.9, 128.6, 116.0, 113.6, 54.9, 49.4, 40.2; EIMS *m/z* 268 (M^+), HRMS calcd for $C_{18}H_{20}O_2$ 268.1463, found 268.1465.

4.1.6. 4-(4,4,4-Triphenyl)-1-butane (6). ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.36–7.18 (m, 15H), 5.76–5.65 (m, 1H), 5.12–4.95 (m, 2H), 3.49 (dt, $J = 1.5$ and 6.6 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 147.3, 135.9, 129.4, 127.7, 125.9, 117.2, 56.2, 45.5; HRMS calcd for $C_{22}H_{20}$ 284.1565, found 284.1566.

4.1.7. 4-(4,4-Diphenyl)-1-pentene (7). ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.46–7.15 (m, 10H), 5.65–5.46 (m, 1H), 5.14–5.02 (m, 2H), 2.97 (d, $J = 6.9$ Hz, 2H), 1.70 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 149.2, 135.1, 127.9, 127.6, 125.6, 117.5, 46.3, 45.8, 27.5; HRMS calcd for $C_{17}H_{18}$ 222.1409, found 222.1408.

4.1.8. 4-Phenyl-1-pentene (8). ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.35–7.16 (m, 5H), 5.81–5.66 (m, 1H), 5.06–4.95 (m, 2H), 2.85–2.78 (m, 1H), 2.47–2.26 (m, 2H), 1.28 (d, $J = 6.9$ Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 147.1, 137.2, 128.3, 126.9, 115.8, 42.6, 39.7, 21.4; EIMS *m/z* 146 (M^+), 105, 91, 77; HRMS calcd for $C_{11}H_{14}$ 146.1096, found 146.1094.

4.1.9. 4-(4-Methoxyphenyl)-1-pentene (9). ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.05 (d, $J = 8.4$ Hz, 2H), 6.79 (d, $J = 8.4$ Hz, 2H), 5.73–5.58 (m, 1H), 4.97–4.88 (m, 2H), 2.73–2.65 (m, 1H), 2.36–2.18 (m, 2H), 1.18 (d, $J = 6.9$ Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 157.7, 138.9, 137.2, 127.7, 115.7, 113.6, 54.9, 42.8, 38.8, 30.6, 21.6; EIMS *m/z* HRMS calcd for $C_{12}H_{16}O$ 176.1201, found 176.1204.

4.1.10. 4-Methyl-4-phenyl-1-pentene (10). ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.40–7.18 (m, 5H), 5.63–5.52 (m, 1H), 5.03–4.94 (m, 2H), 2.39 (dt, $J = 1.2$ and 7.2 Hz, 2H), 1.34 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 149.2, 135.5, 128.1, 125.8, 125.5, 116.9, 48.8, 37.6, 28.5; EIMS *m/z* 160 (M^+), 119, 91, 77; HRMS calcd for $C_{12}H_{16}$ 160.1252, found 160.1254.

4.1.11. 1-Allyl-1,2,3,4-tetrahydronaphthalene (11). ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.47–6.94 (m, 4H), 5.87–5.73 (m, 1H), 5.06–4.98 (m, 2H), 2.88–2.22 (m, 5H), 1.80–1.62 (m, 4H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 140.4, 137.4, 137.1, 129.1, 128.5, 125.5, 116.1, 41.3, 37.3, 29.7, 27.2, 19.5; EIMS *m/z* 172 (M^+), 131, 77; HRMS calcd for $C_{13}H_{16}$ 172.1252, found 172.1250.

4.1.12. 1-Allylacenaphthalene (12). ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.66–7.61 (m, 2H), 7.52–7.45 (m, 2H), 7.34–7.29 (m, 2H), 5.99–5.85 (m, 1H), 5.20–5.08 (m, 2H), 3.85–3.77 (m, 1H), 3.62–3.53 (m, 1H), 3.17–3.10 (m, 1H), 2.76–2.66 (m, 1H), 2.51–2.40 (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 148.7, 144.4, 138.6, 136.5, 131.4, 127.8, 127.7, 122.7, 122.3, 119.2, 118.9, 116.5, 42.6, 40.6, 36.9; EIMS *m*/*z* 194 (M^+), 153, 77; HRMS calcd for $C_{15}H_{14}$ 194.1096, found 196.1098.

4.1.13. 1,3-Diphenyl-1-butyne (13). ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.45–7.12 (m, 10H), 3.87 (q, $J = 7.2$ Hz, 1H), 1.46 (d, $J = 7.2$ Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 143.2, 131.4, 130.1, 128.5, 128.2, 127.7, 126.8, 123.6, 92.6, 82.5, 32.5, 24.3; EIMS *m*/*z* 206 (M^+), 191, 189, 77; HRMS calcd for $C_{16}H_{14}$ 206.1096, found 206.1093.

Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tetlet.2005.09.161.

References and notes

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14. Mostly polymeric product was observed; the similar observation was reported.[4,5]
15. The reaction was carried out in dichloromethane (2 mL), alcohol (1 mmol), alkynylsilane (2 mmol), $BiCl_3$ (5 mol %) at reflux temperature. However, other silyl nucleophiles such as phenyltrimethylsilane did not work.