JOC Note

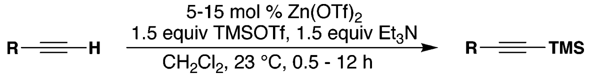
Zinc-Catalyzed Silylation of Terminal Alkynes

Ronald J. Rahaim, Jr.[‡] and Jared T. Shaw*[,†]

Broad Institute of Harvard and MIT Program in Chemical Biology, 7 Cambridge Center, Cambridge, Massachusetts 02142

shaw@chem.ucdavis.edu

Received November 28, 2007

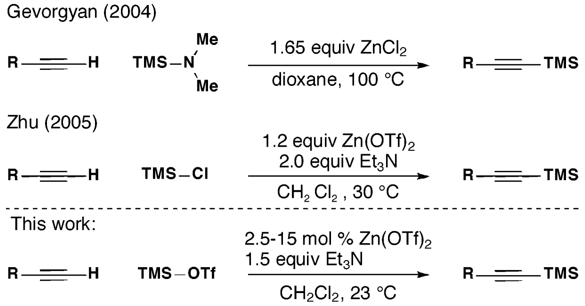


A rapid and high-yielding silylation of terminal alkynes employing TMSOTf and catalytic quantities of $Zn(OTf)_2$ has been developed. The reaction works well for a variety of substrates including reactive esters. Fifteen examples with yields of >90% are reported.

The increasing importance of preparing complex terminal alkynes for applications in multistep synthesis and biological experiments requires new methods for the preparation of alkynylsilanes. Alkynylsilanes are versatile starting materials[1] that are utilized in Hiyama couplings,[2] metathesis reactions,[3] Lewis acid catalyzed alkynylations,[4] and as protected forms of terminal alkynes.[5] Preparation of silylalkynes is routinely done by deprotonation of terminal alkynes with organolithium, or Grignard reagents, followed by addition of a silyl electrophile. The high nucleophilicity of lithium and magnesium acetylides limits functional group compatibility of this reaction.

Recent efforts to solve this problem have focused on the use of less nucleophilic metal acetylides.[6] Silylation of 1-alkynes takes place with excess zinc powder,[7] or in situ prepared activated zinc,[8] and silyl chlorides in acetonitrile at elevated temperature in a sealed tube. To increase the practicality of this route, Gevorgyan developed a direct silylation of terminal alkynes using super-stoichiometric quantities of $ZnCl_2$ and aminosilanes, in 1,4-dioxane at 100 °C (Scheme 1).[9] This protocol demonstrated tolerance of base- and nucleophile-sensitive functional groups but still has the drawback of requiring stoichiometric amounts of a zinc halide and elevated reaction temperature. A lower temperature reaction employing $Zn(OTf)_2$ and trialkylsilyl chlorides was reported, but this method also requires stoichiometric amounts of zinc and was not reported to tolerate a wide variety of functional groups.[10] Herein we report the first zinc-catalyzed silylation of terminal alkynes.[11,12]

SCHEME 1. Protocols for the Silylation of Terminal Alkynes with Zinc



We reasoned the catalysis of alkyne silylation could result from matching the counterion of the zinc catalyst with the leaving group on silicon. $Zn(OTf)_2$ is often the best catalysts for generation of zinc alkynylides.[13] Trapping of these intermediates with a trialkylchlorosilane would liberate chloride and ultimately generate $ZnCl_2$, which is not sufficiently reactive to re-enter the catalytic cycle. Use of a trialkylsilyl triflate would ensure regeneration of $Zn(OTf)_2$ and thus allow a process that is catalytic in zinc (Scheme 2).

Initial investigations began with 4-ethynyltoluene as a test substrate. A variety of solvents and bases were screened using 10 mol % of $Zn(OTf)_2$ and 1.5 equiv of TMSOTf (Table 1). Using Zhu's silylation protocol[10] as a reference point, dichlo-

---

[†] Current address: Department of Chemistry, University of California, One Shields Avenue, Davis, CA 05616.

[‡] Current address: Department of Chemistry and Biochemistry, Scripps-Florida, Jupiter, FL 33458.

[1] (a) Dunetz, J. R.; Danheiser, R. L. *J. Am. Chem Soc.* **2005**, *127*, 5776−5777. (b) Kamijo, S.; Jin, T.; Yamamoto, Y. *Tetrahedron Lett.* **2003**, *44*, 689−691. (c) Trost, B. M.; Machacek, M.; Schnaderbeck, M. J. *Org. Lett.* **2000**, *2*, 1761−1764. (d) Kwon, W.; Sakamoto, K.; Kabuto, C.; Kira, M. *Chem. Lett.* **2000**, 1416−1417. (e) Louw, J.; Baan, J. L.; Kanter, F. J. J.; Bickelhaupt, F.; Klumpp, G. W. *Tetrahedron* **1992**, *48*, 6087−6104. (f) Fallon, G. D.; Fitzmaurice, N. J.; Jackson, W. R.; Perlmutter, P. *Chem. Commun.* **1985**, 4−5. (g) Westmijze, H.; Kleijn, H.; Vermeer, P. *J. Organomet. Chem.* **1984**, *276*, 317−323.

[2] (a) Hatanaka, Y.; Hiyama, T. *J. Org. Chem.* **1988**, *53*, 918−920. (b) Hatanaka, Y.; Hiyama, T. *Tetrahedron Lett.* **1990**, *31*, 2719−2722. (c) Hatanaka, Y.; Hiyama, T. *Synlett* **1991**, 845−853.

[3] (a) Wang, J.; Gurevich, Y.; Botoshansky, M.; Eisen, M. S. *J. Am. Chem. Soc.* **2006**, *128*, 9350−9351. (b) Kim, M.; Park, S.; Maifeld, S. V.; Lee, D. *J. Am. Chem. Soc.* **2004**, *126*, 10242−10243. (c) Baba, T.; Kato, A.; Takahashi, H.; Toriyama, F.; Handa, H. Ono, Y.; Sugisawa, H. *J. Catal.* **1998**, *176*, 488−494.

[4] (a) Hayashi, M.; Inubushi, A.; Mukaiyama, T. *Bull. Chem. Soc. Jpn.* **1988**, *61*, 4037−4042. (b) Chan, T. H.; Fleming, I. *Synthesis* **1979**, 761−786. (c) Utimoto, K.; Tanaka, M.; Kitai, M.; Nozaki, H. *Tetrahedron Lett.* **1978**, *19*, 2301−2304.

[5] Greene, T. W.; Wuts, P. G. M. In *Protective Groups in Organic Synthesis*, 3rd ed.; Wiley: New York, 1999; pp 654−659.

[6] Yamaguchi, M.; Hayashi, A.; Minami, T. *J. Org. Chem.* **1991**, *56*, 4091−4092.

[7] Sugita, H.; Hatanaka, Y.; Hiyama, T. *Tetrahedron Lett.* **1995**, *36*, 2769−2772.

[8] Sugita, H.; Hatanaka, Y.; Hiyama, T. *Synlett* **1996**, 637−639.

[9] Andreev, A. A.; Konshin, V. V.; Komarov, N. V.; Rubin, M.; Brouwer, C.; Gevorgyan, V. *Org. Lett.* **2004**, *6*, 421−424.

[10] Jiang, H.; Zhu, S. *Tetrahedron Lett.* **2005**, *46*, 517−519.

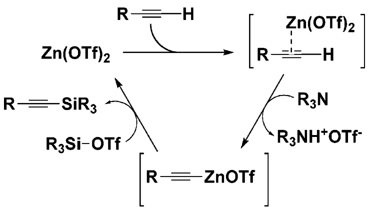
[11] A related reaction using AgCl (0.1 equiv), TMSCl, and DBU has been reported: Taniguchi, Y.; Inanaga, J.; Yamaguchi, M. *Bull. Chem. Soc. Jpn.* **1981**, *54*, 3229−3230.

[12] Several examples of catalytic dehydrogenative silylation of alkynes using a variety of metal catalysts have been reported, albeit with modest yield and substrate tolerance. Yb: (a) Takaki, K.; Komeyama, K.; Takehira, K. *Tetrahedron Lett.* **2003**, *59*, 10381−10395. (b) Takaki, K.; Kurioka, M.; Kamata, T.; Takehira, K.; Makioka, Y.; Fujiwara, Y. *J. Org. Chem.* **1998**, *63*, 9265−9269. Pt: (c) Voronkov, M. G.; Ushakova, N. I.; Tsykhanskaya, I. I.; Pukhnarevich, V. B. *J. Organomet. Chem.* **1984**, *264*, 39−48. CuCl: (d) Liu, H. Q.; Harrod, J. F. *Can. J. Chem.* **1990**, *68*, 1100−1105. MgO: (e) Itoh, M.; Mitsuzuka, M.; Utsumi, T.; Iwata, K.; Inoue, K. *J. Organomet. Chem.* **1994**, *476*, *C30−C31*. (f) Itoh, M.; Mitsuzuka, M.; Iwata, K.; Inoue, K. *Macromolecules* **1994**, *27*, 7917−7919.

[13] Fassler, R.; Tomooka, C. S.; Frantz, D. E.; Carreira, E. M. *Proc. Natl. Acad. Sci. U.S.A.* **2004**, *101*, 5843−5845.

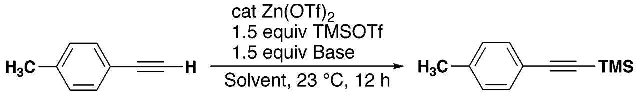
10.1021/jo702557d CCC: $40.75

SCHEME 2. Proposed Catalytic Cycle for Zinc Silylation of Terminal Alkynes



romethane and triethylamine were tested first, affording the silylated alkyne quantitatively (entry 1). Toluene (entry 2), 1,4-dioxane (entry 4), and diethyl ether (entry 5) also afforded the silylalkyne in high yield. Reducing the amount of TMSOTf or Et_3N to 1.1 equiv reduced the yield (entries 9 and 10). Concomitantly lowering the TMSOTf and Et_3N concentration to 1.1 equiv lowered the yield even further to 80%. The efficiency of the reaction was directly affected by the choice of base (entries 1 and 11−14), with triethylamine providing the best results. Next the catalyst concentration was varied. As little as 2.5 mol % of $Zn(OTf)_2$ could be employed (entry 16), but further reduction (1 mol %) eroded the yield. When silylation is attempted in the absence of $Zn(OTf)_2$ (entry 18), the starting material is recovered, substantiating the idea that the silylation is catalyzed by zinc.

TABLE 1. Optimization of $Zn(OTf)_2$-Catalyzed Silylation



entry	solvent	base	mol % of $Zn(OTf)_2$	% yield[a]
1	CH_2Cl_2	Et_3N	10	100
2	toluene	Et_3N	10	87
3	THF	Et_3N	10	14
4	1,4-dioxane	Et_3N	10	100
5	Et_2O	Et_3N	10	100
6	CH_3CN	Et_3N	10	46
7	EtOAc	Et_3N	10	49
8	DMF	Et_3N	10	40
9	CH_2Cl_2	Et_3N	10	84[b]
10	CH_2Cl_2	Et_3N	10	80[b,c]
11	CH_2Cl_2	*i*-Pr_2NEt	10	81
12	CH_2Cl_2	pyridine	10	4
13	CH_2Cl_2	2,6-lutidine	10	29
14	CH_2Cl_2	PS[d]	10	0
15	CH_2Cl_2	Et_3N	5	98
16	CH_2Cl_2	Et_3N	2.5	99
17	CH_2Cl_2	Et_3N	1	62
18	CH_2Cl_2	Et_3N	0	0

[a] Determined by GC/MS with biphenyl as an internal standard. [b] With 1.1 equiv of TMSOTf. [c] With 1.1 equiv of Et_3N. [d] PS = proton sponge (1,8-bis(dimethylamino)naphthalene).

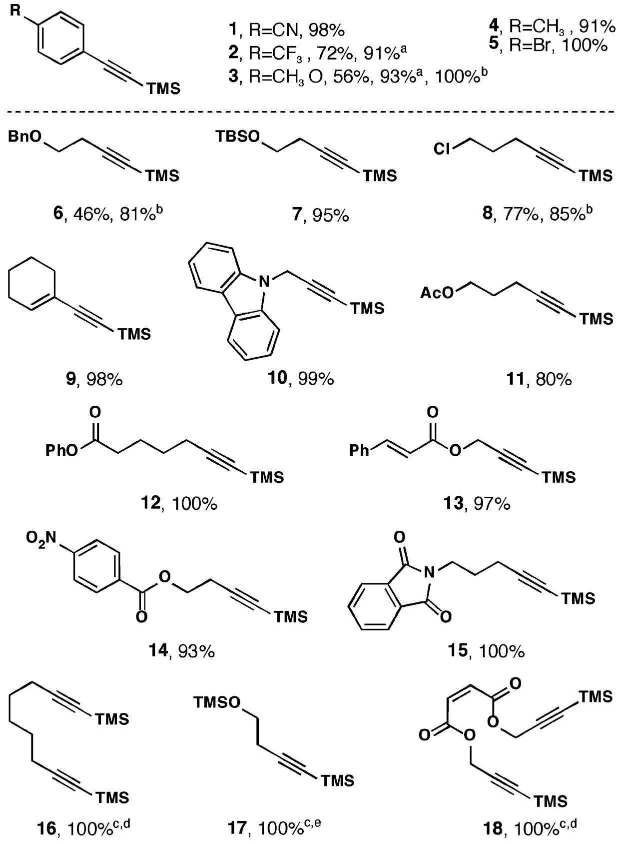


FIGURE 1. Silylation of alkynes (1 mmol) with 5 mol % of $Zn(OTf)_2$, 1.5 equiv of TMSOTf, and 1.5 equiv of Et_3N in CH_2Cl_2 (4 mL) at 23 °C for 12 h. Yield given for isolated material after flash chromatography: [a]10 mol % of $Zn(OTf)_2$; [b]15 mol % of $Zn(OTf)_2$; [c]3.0 equiv of TMSOTf and 3.0 equiv of Et_3N; [d]prepared from the corresponding diyne; [e]prepared form 3-butyne-1-ol.

A variety of substrates were examined using the optimized conditions (Figure 1). Wide substrate tolerance was observed. Silylation of a series of substituted phenyl acetylenes revealed that introduction of a modestly electron-withdrawing group (CF_3) or an electron-donating group (CH_3O) reduced the yield. An increase in catalyst loading to 10 or 15 mol % increased the yield in these cases. High yields of products containing phenyl (12%), cinnamoyl (13%), and *p*-nitrobenzoyl (14%) esters were observed. Disilylation of 1,8-nonadiyne and 3-butene-1-ol were possible by doubling the quantity of TMSOTf and base, providing **16** and **17** each in quantitative yield. Finally, the nucleophile-sensitive dipropargyl maleate was disilylated in 100% yield, providing an improved yield of **18** when compared to the method of Gevorgyan (68%).

Several reports have indicated that the source of $Zn(OTf)_2$ can affect the reactions of the resulting zinc alkynylides. In the case of aldehyde alkynylation,[14] there are several instances in the literature that state that the source of $Zn(OTf)_2$ can affect the yield of the reaction.[15] We found that $Zn(OTf)_2$ purchased from Aldrich and Strem showed the same reactivity for substrates that afforded >90% yield with 5 mol % catalyst. Some variability was observed for the more problematic substrates. For example, subjection of 5-chloro-1-pentyne to the reaction conditions with 15 mol % of $Zn(OTf)_2$ from Aldrich increased the yield of silylalkyne to 85%, whereas the use of 15 mol % of $Zn(OTf)_2$ from Strem lowered the yield to 38%.

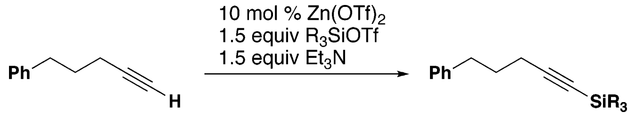
The steric constraints of the silyl triflate had a dramatic effect on the efficiency of the reaction (Table 2). 5-Phenyl-1-pentyne was readily silylated in excellent yield under the standard reaction conditions. Replacement of TMSOTf with triethylsilyl triflate (TESOTf) provided a modest yield of the expected product (entry 2). The yield was significantly increased when

---

[14] Frantz, D. E.; Fassler, R.; Tomooka, C. S.; Carreira, E. M. *Acc. Chem. Res.* **2000**, *33*, 373−381.

[15] Kirkham, J. E. D.; Courtney, T. D. L.; Lee, V.; Baldwin, J. E. *Tetrahedron* **2005**, *61*, 7219−7232 and references cited therein.

TABLE 2. Screening of Silyl Triflates



entry	R_3SiOTf	solvent	temp	% yield[a]
1	TMSOTf	CH_2Cl_2	23 °C	100
2	TESOTf	CH_2Cl_2	23 °C	50
3	TESOTf	toluene	80 °C	100
4	Et_3SiH + TfOH	toluene	80 °C	94
5	TBSOTf	CH_2Cl_2	23 °C	20
6	TBSOTf	toluene	80 °C	45
7	TIPSOTf	toluene	80 °C	0
8	$Me_2SiHOTf$[b]	CH_2Cl_2	23 °C	86

[a] Isolated yields after flash chromatography. [b] Prepared from $Ph(Me)_2SiH$ and TfOH; see ref 16.

dichloromethane was replaced with toluene and the reaction mixture was heated to 80 °C (entry 3). Use of *tert*-butyldimethylsilyl triflate (TBSOTf) afforded the TBS alkyne in only 45% yield with the modified protocol (entry 6), whereas triisopropylsilyl triflate (TIPSOTf) failed (entry 7). It was also determined that TESOTf could be prepared in situ[16] (entry 4). We used this protocol to prepare dimethylsilyltriflate, prepared from the corresponding silane,[17] which yielded the alkynylsilane product in high yield. Gevorgyan's[9] reaction shows a similar trend in the reactivity of sterically demanding silylating agents.

In conclusion, we have demonstrated the first catalytic conditions for silylation of terminal alkynes. The reaction is extremely efficient for introduction of several synthetically useful trialkylsilyl groups and avoids the use of stoichiometric quantities of strong bases and metal mediators.

Experimental Section

General Procedure for the Silylation of Terminal Alkynes: A round-bottom flask was charged with zinc triflate (0.05 mmol, 0.018 g) and sealed with a septum under an atmosphere of argon. An argon inlet was attached followed by the sequential addition of dry CH_2Cl_2 (4.2 mL), dry triethylamine (1.5 mmol, 0.209 mL), the alkyne (1 mmol), and TMSOTf (1.5 mmol, 0.271 mL). The reaction was stirred until complete as judged by TLC (approximately 12 h) then quenched with saturated NH_4Cl. The mixture was extracted with ether; the aqueous layer was back extracted with ether, and the combined organics were dried, filtered, and concentrated. The crude material was then subjected to flash chromatography.

4-((Trimethylsilyl)ethynyl)benzonitrile (1): Subjection of 4-ethynylbenzonitrile (1 mmol, 0.127 g) to the general silylation procedure afforded 0.1947 g (98%) of 4-((trimethylsilyl)ethynyl)benzonitrile as a light yellow solid after flash chromatography (hexanes/Et_2O: 90/10): ^1H NMR (500 MHz, $CDCl_3$) δ 7.58 (d, $J = 8.52$ Hz, 2H), 7.52 (d, $J = 8.52$ Hz, 2H), 0.25 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 132.3, 131.8, 127.9, 118.3, 111.7, 102.9, 99.5, −0.3. Physical and spectral data were consistent with literature precedent.[18]

((4-Bromophenyl)ethynyl)trimethylsilane (5): Subjection of 1-bromo-4-ethynylbenzene (1 mmol, 0.181 g) to the general silylation procedure afforded 0.2531 g (100%) of ((4-bromophenyl)ethynyl)trimethylsilane as a light yellow solid. The crude material was analytically pure by ^1H NMR, so flash chromatography was not performed: ^1H NMR (300 MHz, $CDCl_3$) δ 7.43 (d, $J = 8.29$ Hz, 2H), 7.31 (d, $J = 8.36$ Hz, 2H), 0.24 (s, 9H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 133.3, 131.4, 122.7, 122.1, 103.8, 95.5, −0.1. Physical and spectral data were consistent with an authentic commercial sample.

9-(3-(Trimethylsilyl)prop-2-ynyl)-9*H*-carbazole (10): Subjection of 9-(prop-2-ynyl)-9*H*-carbazole (1 mmol, 0.205 g) to the general silylation procedure afforded 0.2773 g (100%) of 9-(3-(trimethylsilyl)prop-2-ynyl)-9*H*-carbazole as a white solid after flash chromatography (hexanes/EtOAc: 95/5): mp 128−129 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 7.98 (d, $J = 7.72$ Hz, 2H), 7.38 (m, 4H), 7.15 (m, 2H), 4.92 (s, 2H), 0.00 (s, 9H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 139.9, 125.7, 123.1, 120.3, 119.3, 108.9, 99.2, 89.2, 33.4, −0.2; IR (neat) 2205, 1330, 837, 747 cm^{-1}; LRMS (EI, 70 eV) 277 (100), 204 (22), 180 (14), 166 (34), 152 (7), 73 (13); HRMS (EI) *m*/*z* calcd for $C_{18}H_{20}NSi$ $(M + Na)^+$ 278.1365, found: 278.1354.

5-(Trimethylsilyl)pent-4-ynyl acetate (11): Subjection of pent-4-ynyl acetate (1 mmol, 0.132 mL) to the general silylation procedure afforded 0.1586 g (80%) of 5-(trimethylsilyl)pent-4-ynyl acetate as a clear oil after flash chromatography (hexanes/Et_2O: 95/5): ^1H NMR (500 MHz, $CDCl_3$) δ 4.14 (t, $J = 6.31$ Hz, 2H), 2.31 (t, $J = 7.04$ Hz, 2H), 2.04 (s, 3H), 1.83 (q, $J = 6.67$ Hz, 2H), 0.14 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 170.8, 105.7, 85.3, 63.1, 27.7, 20.8, 16.6, 0.1; IR (neat) 2959, 2175, 1741, 1234, 837, 758 cm^{-1}; LRMS (EI, 70 eV) 198 (1), 197 (9), 139 (18), 138 (100), 125 (32), 73 (100), 66 (30), 59 (18); HRMS (EI) *m*/*z* calcd for $C_{10}H_{18}O_2SiNa$ $(M + Na)^+$ 221.0974, found 221.0971.

Phenyl 7-(trimethylsilyl)hept-6-ynoate (12): Subjection of phenyl hept-6-ynoate (1 mmol, 0.195 mL) to the general silylation procedure afforded 0.2741 g (100%) of phenyl 7-(trimethylsilyl)-hept-6-ynoate as a clear oil after flash chromatography (hexanes/Et_2O: 90/10): ^1H NMR (300 MHz, $CDCl_3$) δ 7.37 (t, $J = 7.65$ Hz, 2H), 7.23 (t, $J = 7.40$ Hz, 2H), 7.08 (d, $J = 7.89$ Hz, 2H), 2.60 (t, $J = 7.39$ Hz, 2H), 2.31 (t, $J = 7.02$ Hz, 2H), 1.87 (quint, $J = 7.54$ Hz, 2H), 1.65 (quint, $J = 7.36$ Hz, 2H), 0.16 (s, 9H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 171.8, 150.7, 129.3, 125.7, 121.5, 106.6, 85.0, 33.8, 27.9, 24.0, 19.5, 0.1; IR (neat) 2172, 1758, 1192, 1125, 837, 757 cm^{-1}; LRMS (EI, 70 eV) 273 (4), 181 (100), 109 (38), 93 (47), 77 (20), 73 (77); HRMS (EI) *m*/*z* calcd for $C_{16}H_{22}O_2SiNa$ $(M + Na)^+$ 297.1287, found 297.1295.

3-(Trimethylsilyl)prop-2-ynyl cinnamate (13): Subjection of prop-2-ynyl cinnamate (1 mmol, 0.186 g) to the general silylation procedure afforded 0.2501 g (97%) of 3-(trimethylsilyl)prop-2-ynyl cinnamate as a clear oil after flash chromatography (hexanes/EtOAc: 95/5): ^1H NMR (500 MHz, $CDCl_3$) δ 7.53 (d, $J = 16.03$ Hz, 1H), 7.31 (m, 2H), 7.18 (m, 3H), 6.26 (d, $J = 16.02$ Hz, 1H), 4.63 (s, 2H), 0.01 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 165.9, 145.6, 134.1, 130.4, 128.8, 128.0, 117.1, 99.0, 92.0, 52.7, −0.3; IR (neat) 1715, 1635, 1151, 838, 760 cm^{-1}; LRMS (EI, 70 eV) 258 (7), 257 (23), 185(5), 145 (14), 131 (100), 103 (51), 77 (31), 73 (84); HRMS (EI) *m*/*z* calcd for $C_{15}H_{19}O_2Si$ $(M + H)^+$ 259.1882, found 259.1879.

4-(Trimethylsilyl)but-3-ynyl 4-nitrobenzoate (14): Subjection of but-3-ynyl 4-nitrobenzoate (1 mmol, 0.219 g) to the general silylation procedure afforded 0.2716 g (93%) of 4-(trimethylsilyl)-but-3-ynyl 4-nitrobenzoate as a light tan solid after flash chromatography (hexanes/EtOAc: 95/5): mp 132−133 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 8.31 (d, $J = 8.82$ Hz, 2H), 8.23 (d, $J = 8.86$ Hz, 2H), 4.47 (t, $J = 6.82$ Hz, 2H), 2.73 (t, $J = 6.82$ Hz, 2H), 0.14 (s, 9H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.3, 150.6, 135.4, 130.7, 123.5, 101.6, 87.0, 63.4, 20.4, −0.06; IR (neat) 2211, 1716, 1522, 1244, 1103, 847, 715 cm^{-1}; LRMS (EI, 70 eV) 276 (87), 224 (100), 178 (14), 134 (9), 104 (54), 76 (39), 73 (19); HRMS (EI) *m*/*z* calcd for $C_{14}H_{18}NO_4Si$ $(M + H)^+$ 292.1005, found 292.1007.

---

(16) TESOTf was prepared by adding triethylsilane to a 1 M solution of TfOH in CH_2Cl_2 at 0 °C. The resultant solution was then added to a mixture of Zn(OTf)2,5-phenyl-1-pentyne, Et_3N, and toluene.

(17) For the preparation of silyl triflates, and a general order of ligand displacement with triflic acid, see: Uhlig, W. *Chem. Ber.* **1996**, *129*, 733−739 and references cited therein.

(18) Dirk, S. M.; Tour, J. M. *Tetrahedron* **2003**, *59*, 287−293.

2-(5-(Trimethylsilyl)pent-4-ynyl)isoindoline-1,3-dione (15): Subjection of 2-(pent-4-ynyl)isoindoline-1,3-dione (1 mmol, 0.213 g) to the general silylation procedure afforded 0.2854 g (100%) of 2-(5-(trimethylsilyl)pent-4-ynyl)isoindoline-1,3-dione as a pale yellow solid after flash chromatography (hexanes/EtOAc: 80/20): mp 78−81 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.82 (dd, $J = 1.35$ and 3.08 Hz, 2H), 7.69 (dd, $J = 0.97$ and 3.08 Hz, 2H), 3.75 (t, $J = 7.06$ Hz, 2H), 2.29 (t, $J = 7.09$ Hz, 2H), 1.91 (quint, $J = 7.09$ Hz, 2H), 0.06 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 168.2, 133.8, 132.1, 123.1, 105.6, 85.2, 37.2, 27.4, 17.6, −0.05; IR (neat) 2200, 1704, 1392, 841, 726 cm^{-1}; LRMS (EI, 70 eV) 285 (5), 270 (100), 153 (2), 146 (2), 130 (30), 73 (37); HRMS (EI) *m/z* calcd for $C_{16}H_{19}NO_2SiNa$ $(M + Na)^+$ 308.1083, found 308.1086.

Trimethyl(4-(trimethylsilyl)but-3-ynyloxy)silane (17): Subjection of 3-butyn-1-ol (1 mmol, 0.076 mL) to the general silylation procedure with 3 equiv of TMSOTf (3 mmol, 0.542 mL) and 3 equiv of triethylamine (3 mmol, 0.418 mL) afforded 0.2139 g (100%) of trimethyl(4-(trimethylsilyl)but-3-ynyloxy)silane as a clear oil after flash chromatography (hexanes/Et_2O: 80/20): ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.56 (t, $J = 7.19$ Hz, 2H), 2.32 (t, $J = 7.19$ Hz, 2H), 0.02 (s, 9H), 0.00 (s, 9H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 103.9, 85.7, 61.2, 24.1, 0.1, −0.4. Physical and spectral data were consistent with literature precedent.[19]

Bis(3-(trimethylsilyl)prop-2-ynyl) maleate (18): Subjection of diprop-2-ynyl maleate (1 mmol, 0.192 g) to the general silylation procedure with 3 equiv of TMSOTf (3 mmol, 0.542 mL) and 3 equiv of Et_3N (3 mmol, 0.418 mL) afforded 0.3365 g (100%) of bis(3-(trimethylsilyl)prop-2-ynyl) maleate as a light yellow solid after flash chromatography (hexanes/Et_2O: 50/50): ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.92 (s, 2H), 4.79 (s, 4H), 0.17 (s, 18H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 163.8, 133.5, 98.0, 92.8, 53.5, −0.4. Physical and spectral data were consistent with literature precedent.[9]

Triethyl(5-phenylpent-1-ynyl)silane (Table 2, entry 3): A round-bottom flask was charged with zinc triflate (0.1 mmol, 0.036 g) and sealed with a septum under an atmosphere of argon. An argon inlet was attached followed by the sequential addition of dry toluene (4 mL), dry triethylamine (1.5 mmol, 0.209 mL), 5-phenyl-1-pentyne (1 mmol, 0.156 mL), and TESOTf (1.5 mmol, 0.339 mL). The round-bottom flask was placed in an oil bath at 80 °C and stirred for 12 h. After the general workup, 0.2583 g (100%) of triethyl(5-phenylpent-1-ynyl)silane was afforded as a clear oil following flash chromatography (hexanes/Et_2O: 99/1): ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.2 (m, 5H), 2.75 (t, $J = 7.61$ Hz, 2H), 2.27 (t, $J = 6.95$ Hz, 2H), 1.85 (quint, $J = 7.28$ Hz, 2H), 1.02 (t, $J = 7.86$ Hz, 9H), 0.60 (q, $J = 7.90$ Hz, 6H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 141.6, 128.5, 128.3, 125.8, 108.1, 82.1, 34.6, 30.4, 19.3, 7.5, 4.5; IR (neat) 2951, 2171, 1455, 1016, 696 cm^{-1}; LRMS (EI, 70 eV) 258 (1), 229 (100), 202 (13), 201 (62), 119 (3), 115 (20), 91 (45); HRMS (EI) *m/z* calcd for $C_{17}H_{26}SiNa$ $(M + Na)^+$ 281.0974, found 281.0972.

Dimethyl(5-phenylpent-1-ynyl)silane (Table 2, entry 8): A round-bottom flask was charged with zinc triflate (0.1 mmol, 0.036 g) and sealed with a septum under an atmosphere of argon. An argon inlet was attached followed by the sequential addition of dry CH_2Cl_2 (3 mL), dry triethylamine (2.0 mmol, 0.279 mL), 5-phenyl-1-pentyne (1 mmol, 0.156 mL), and a 0.91 M solution of dimethylsilyl triflate (1.5 mmol, 1.65 mL). The 0.91 M solution of dimethylsilyl triflate was prepared by the dropwise addition of phenyldimethylsilane (3 mmol, 0.46 mL) to triflic acid (1 M in CH_2Cl_2, 3.3 mmol, 3.3 mL) at 0 °C. After complete addition of phenyldimethylsilane, the reaction was warmed to room temperature and used directly. Following the general workup procedure, 0.1738 g (86%) of dimethyl(5-phenylpent-1-ynyl)silane was afforded as a clear oil after flash chromatography (hexanes/Et_2O: 95/5): ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.30 (m, 5H), 4.20 (s, 1H), 2.78 (t, $J = 7.56$ Hz, 2H), 2.30 (t, $J = 7.05$ Hz, 2H), 1.90 (quint, $J = 7.31$ Hz, 2H), 0.3 (s, 6H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 141.5, 128.5, 128.3, 125.9, 108.6, 82.0, 34.7, 30.0, 19.3, −2.7; IR (neat) 2954, 2175, 2133, 1249, 878 cm^{-1}; LRMS (EI, 70 eV) 202 (9), 187 (22), 186 (3), 185 (15), 143 (33), 119 (1), 105 (17), 104 (100), 91 (40), 59 (22); HRMS (EI) *m/z* calcd for $C_{13}H_{19}Si$ $(M + H)^+$ 203.1256, found 203.1263.

Acknowledgment. This research was funded by the Broad Institute Scientific Planning and Allocation of Resources Committee (SPARC). Dr. John Greaves (University of California, Irvine) is acknowledged for obtaining mass spectral data, and Dr. Yuchen Tang (University of California, Davis) is acknowledged for assistance in preparing this manuscript.

Supporting Information Available: Experimental details, product characterization data, and ^{1}H and ^{13}C NMR spectra for compounds **1**−**18**, and Table 2 entries 3 and 8. This material is available free of charge via the Internet at http://pubs.acs.org.

JO702557D

---

(19) Markó, I. E.; Bayston, D. J. *Tetrahedron* **1994**, *50*, 7141−7156.