A Mild and General Approach to the Preparation and Trapping of Highly Reactive Formylsilanes

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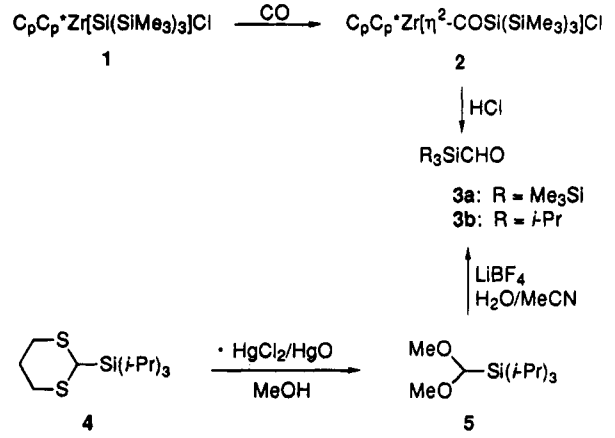
Acylsilanes have drawn a great deal of attention in the last decade due to their interesting reactivities and diverse applications in organic synthesis.[1-4] A variety of methods have been developed for their synthesis and have been thoroughly reviewed.[3] Although early reports[5] indicated hydrolytic instability for an organosilicon structure having a carbonyl group directly bound to silicon, many acylsilanes have been shown to be fairly stable. On the other hand, the chemistry of formylsilanes has remained largely unexplored due to their reactivity. There are five reports of the isolation or trapping of formylsilanes, which describe four independent synthetic approaches.

Tilley *et al.*[6] reported that treatment of zirconium η^2-silaacyl complex **2** with anhydrous HCl gas in toluene gave formyltris(trimethylsilyl)silane (**3a**) in 55% yield (Scheme 1). Formyltriisopropylsilane (**3b**) was prepared by Soderquist *et al.*[7] *via* a modified three-step dithiane method: treatment of 1,3-dithiane with butyllithium followed by triisopropylsilyl chloride yielded 2-(triisopropylsilyl)dithiane (**4**). This was then treated with $HgCl_2$/HgO in methanol to afford the dimethyl acetal of formyltriisopropylsilane which was hydrolyzed to give formyltriisopropylsilane (85% overall) (Scheme 1).

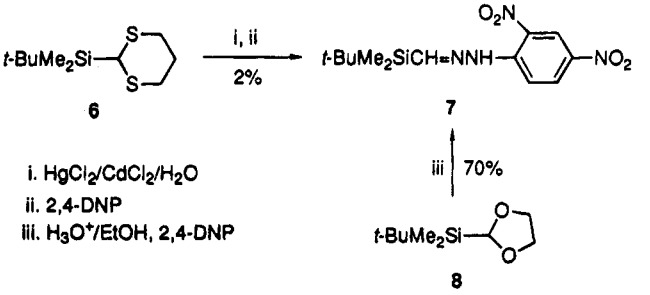
Silverman *et al.*[8] found that hydrolysis of 2-*tert*-butyldimethylsilyl)dithiane (**6**) under normal dithiane hydrolysis conditions, followed by treatment of the reaction mixture with 2,4-DNP reagent, gave the 2,4-dinitrophenylhydrazone of formyl-*tert*-butyldimethylsilane (**7**) in only 2% yield. In contrast to this, a 70% yield was obtained when 2-*tert*-butyldimethylsilyl)dioxolane (**8**) was hydrolyzed under mild acidic conditions in the presence of 2,4-dinitrophenylhydrazine (Scheme 2). Formyltrimethylsilane was captured by Ireland *et al.*[9] and by Linderman *et al.*[10] who carried out the Swern oxidation of (trimethylsilyl)methanol and isolated the products of nucleophilic attack by organometallics on the formyltrimethylsilane intermediate.

Although formyltris(trimethylsilyl)silane and formyltriisopropylsilane have been found to be thermally stable, they are extremely sensitive to air, both decomposing violently upon exposure to atmospheric oxygen (even igniting spontaneously for $(i\text{-Pr})_3SiCHO$).[7] The instability of formylsilanes is further reflected in the high sensitivity of their synthetic yields to the reaction conditions.

Scheme 1



Scheme 2



Results and Discussion

Our previous work[11-13] has demonstrated the use of (benzotriazol-1-yl)(carbazol-9-yl)methane (**9**) as a versatile formyl anion equivalent. The convenient reactivity of the anion of **9** toward a wide spectrum of electrophiles and the mild acidic conditions used for the hydrolysis of the intermediate products have prompted us to investigate the possibility of this system in the synthesis of formylsilanes.

Thus, treatment of **9** with butyllithium at −78 °C for 2 h followed by silyl chlorides afforded the corresponding silylated products **10a–f** in excellent yields (Scheme 3 and Table 1). The insensitivity of the reaction to steric and/or electronic (alkyl or aryl) effects of the substituents in the silyl chlorides was testimony to the generality of this reaction. In most cases, the crude products obtained were virtually pure (TLC and NMR) and could be used for the subsequent hydrolysis without further purification. Compounds **10a–f** were characterized by ^1H and ^{13}C NMR spectroscopy and their elemental analysis data.

Hydrolysis of the intermediate products **10a–f** was carried out in dilute sulfuric acid in the presence of 2,4-dinitrophenylhydrazine. In the cases of **10a–d**, the reactions went to completion at room temperature within 24 h and afforded the 2,4-dinitrophenylhydrazones of the

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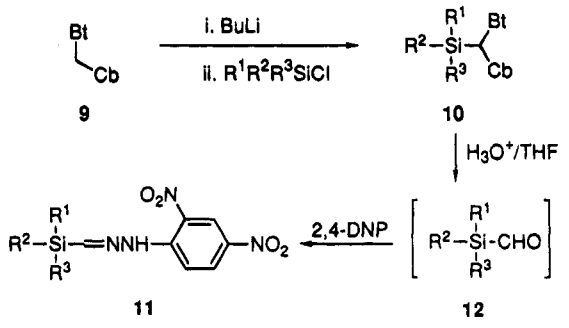
Scheme 3



For 10, 11 and 12: a. $R^1 = R^2 = R^3 = Me$
b. $R^1 = R^2 = Me$; $R^3 = t$-Bu
c. $R^1 = R^2 = R^3 = i$-Pr
d. $R^1 = R^2 = R^3 = i$-Bu
e. $R^1 = R^2 = Ph$; $R^3 = t$-Bu
f. $R^1 = R^2 = R^3 = Ph$

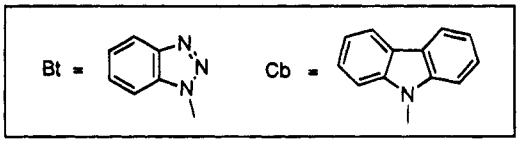


Table 1. Preparation of Intermediate Products 10a–f

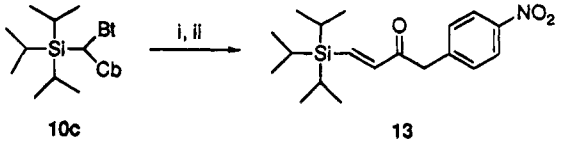
compd	yield (%)	mp (°C)	recryst solvent	molecular formula	found (calcd) C	H	N
10a	91	185–186	methanol	$C_{22}H_{22}N_4Si$	71.22 (71.32)	5.99	15.08 (15.13)
10b	89	166–168	hexane	$C_{25}H_{28}N_4Si$	72.63 (72.77)	6.86	13.56 (13.58)
10c	92	130–131	hexane	$C_{28}H_{24}N_4Si$	74.09 (73.97)	7.53	12.32 (12.33)
10d	90	117–118	methanol	$C_{31}H_{40}N_4Si$	75.14 (74.95)	8.20	11.33 (11.28)
10e	78	201–202	methanol	$C_{35}H_{32}N_4Si$	78.14 (78.32)	6.06	10.37 (10.44)
10f	95	237–238	methanol	$C_{37}H_{28}N_4Si$	79.98 (79.83)	5.07	10.07 (10.07)

Table 2. Preparation of 2,4-Dinitrophenylhydrazones 11a–f

compd	yield (%)	mp (°C)	lit. mp (°C)	found (calcd) C	H	N
11a	48	135–136	141–142[8]	42.91 (42.54)	4.94	20.12 (19.84)
11b	81	137–138	139–140[8]	47.91 (48.13)	6.17	17.22 (17.27)
11c	79	111–112	109–111[7]	52.37 (52.44)	7.13	15.37 (15.29)
11d	84	145–146		55.95 (55.86)	7.88	13.56 (13.71)
11e	61	146–147		61.51 (61.59)	5.41	12.54 (12.49)
11f	58	173–174		63.80 (64.09)	4.26	11.96 (11.96)

corresponding formylsilanes (**11a–d**) (Scheme 3 and Table 2). The low yield of **11a** was presumably attributed to the much lower stability of free formyltrimethylsilane. Attempts to hydrolyze compounds **10e** and **10f** under similar conditions resulted in recovery of most of the starting material, presumably because the electron-withdrawing nature of the phenyl group disfavored the formation of the intermediate imminium ion (for hydrolysis mechanism see ref 11). However, when the hydrolysis was carried out at 55–60 °C, the 2,4-dinitrophenylhydrazones of formyl-*tert*-butyldiphenylsilane (**11e**) and formyltriphenylsilane (**11f**) were obtained in yields of 61% and 58%, respectively. To assess the stability of formylsilanes, such as formyltriisopropylsilane, compound **10c** was subjected to the same hydrolysis conditions as described above for **10a–d** except that 2,4-dinitrophenylhydrazine was not initially added to the reaction mixture. After **10c** was completely consumed (as indicated by TLC), 2,4-dinitrophenylhydrazine was added and the mixture stirred at room temperature for an additional 4 h. In this case, the 2,4-dinitrophenylhydrazone of formyltriisopropylsilane (**11c**) was obtained in 41% yield, indicating the partial decomposition of formyltriisopropylsilane under these conditions.

Scheme 4[a]



[a] Key: (i) H_2SO_4, THF/H_2O, rt, 24 h; (ii) NaOH until pH = 11–12; 4-nitroacetophenone.

The formylsilanes prepared by this method have also been shown to react with other nucleophiles, as exemplified by 4-nitroacetophenone, under normal basic conditions (Scheme 4), indicating the considerable potential utility of these highly reactive species.

In conclusion, we have developed a novel approach to the formation and trapping of various substituted formylsilanes by using (benzotriazol-1-yl)(carbazol-1-yl)methane as a formyl anion equivalent. The present method is advantageous in terms of simplicity and generality as demonstrated by the good overall yields and the diversity of silyl chlorides that can be used. The mild hydrolysis conditions avoid the use of toxic reagents and allow a wide range of formylsilane derivatives to be readily accessible.

Experimental Section

For general experimental techniques, see our previous papers.[11–13] (Benzotriazol-1-yl)(carbazol-9-yl)methane (**9**) was prepared by a literature procedure: mp 193–5 °C (lit.[11] mp 193–5 °C).

Lithiation of (Benzotriazol-1-yl)(carbazol-9-yl)methane (9) and Reaction with Electrophiles. General Procedure. *n*-BuLi (2.5 M in hexane; 4.4 mL, 11 mmol) was added to a solution of (benzotriazol-1-yl)(carbazol-9-yl)methane (**9**) (2.98 g, 10 mmol) in dry THF (80 mL) at −78 °C. The solution was stirred at −78 °C for 2 h, and then the appropriate silyl chloride (11 mmol) in THF (10 mL) was added. The mixture was stirred at −78 °C for 4 h and then at room temperature for 12 h. The reaction mixture was poured into saturated aqueous NH_4Cl (40 mL) and the aqueous layer extracted with diethyl ether (3 × 30 mL). The combined organic layers were washed with water (1 × 25 mL) and dried ($MgSO_4$) and the solvent evaporated under reduced pressure to afford the crude products which were then purified to give analytically pure products (Table 1).

(Benzotriazol-1-yl)(carbazol-9-yl)(trimethylsilyl)-methane (10a). ^1H NMR ($CDCl_3$): δ 8.58–7.92 (m, 4H), 7.85–7.50 (m, 2 H), 7.45–6.95 (m, 7 H), 0.35 (s, 9 H). ^{13}C NMR ($CDCl_3$): δ 145.2, 139.5, 133.0, 132.1, 127.9, 127.8, 126.2, 124.4, 124.3, 122.8, 120.44, 120.38, 120.32, 119.6, 119.5, 119.4, 110.5, 110.12, 110.06, 60.2, 1.8.

(Benzotriazol-1-yl)(*tert*-butyldimethylsilyl)(carbazol-9-yl)methane (10b). ^1H NMR ($CDCl_3$): δ 8.10 (d, 1 H, J = 7.8 Hz), 7.99 (d, 2 H, J = 7.6 Hz), 7.78 (d, 1 H, J = 8.3 Hz), 7.65 (t, 1 H, J = 7.8 Hz), 7.61 (d, 1 H, J = 8.3 Hz), 7.32 (t, 1 H, J = 7.3 Hz), 7.27–7.10 (m, 5 H), 6.95 (s, 1 H), 0.89 (s, 9 H), 0.71 (s, 3 H), 0.0 (s, 3 H). ^{13}C NMR ($CDCl_3$): δ 145.8, 140.2, 139.2, 133.4,

127.8, 126.2, 125.8, 124.2, 123.6, 123.1, 120.9, 120.0, 119.9, 119.8, 111.9, 109.6, 107.8, 58.0, 27.0, 17.4, −2.6.

(Benzotriazol-1-yl)(carbazol-9-yl)(triisopropylsilyl)-methane (10c). ^{1}H NMR ($CDCl_3$): δ 8.09 (d, 1 H, J = 7.8 Hz), 7.96 (d, 2 H, J = 8.1 Hz), 7.85 (d, 1 H, J = 8.3 Hz), 7.65 (t, 1 H, J = 8.3 Hz), 7.59 (d, 1 H, J = 8.3 Hz), 7.32 (t, 1 H, J = 8.0 Hz), 7.26−7.10 (m, 5 H), 7.09 (s, 1 H), 1.61 (heptet, 3 H, J = 7.5 Hz)), 1.05 (d, 9 H, J = 7.5 Hz), 1.02 (d, 9 H, J = 7.5 Hz). ^{13}C NMR ($CDCl_3$): δ 145.9, 140.3, 139.3, 133.1, 127.8, 126.0, 125.7, 124.2, 123.6, 123.3, 120.8, 120.0, 119.9, 119.8, 111.7, 109.7, 108.2, 58.0, 18.8, 18.6, 12.2.

(Benzotriazol-1-yl)(carbazol-9-yl)(triisobutylsilyl)-methane (10d). ^{1}H NMR ($CDCl_3$): δ 8.15−7.88 (m, 3 H), 7.80−7.50 (m, 2 H), 7.42−6.91 (m, 7 H), 6.89 (s, 1 H), 1.87−1.69 (m, 3 H), 1.07 (dd, 3 H, J_1 = 15.1 Hz and J_2 = 6.3 Hz), 0.88 (dd, 3 H, J_1 = 15.1 Hz and J_2 = 6.3 Hz), 0.89 (d, 9 H, J = 6.3 Hz), 0.75 (d, 9 H, J = 6.3 Hz). ^{13}C NMR ($CDCl_3$): δ 145.8, 140.3, 139.2, 133.2, 127.7, 126.2, 126.1, 124.2, 123.9, 123.8, 120.8, 119.9, 119.8, 111.4, 109.6, 108.0, 60.4, 26.49, 26.46, 24.5, 24.4.

(Benzotriazol-1-yl)(*tert*-butyldiphenylsilyl)(carbazol-9-yl)methane (10e). ^{1}H NMR ($CDCl_3$): δ 8.01 (d, 1 H, J = 7.6 Hz), 7.97−7.75 (m, 5 H), 7.70−7.45 (m, 4 H), 7.42−7.10 (m, 10 H), 7.02−6.85 (m, 2 H), 6.73−6.60 (m, 1 H), 0.99 (s, 9 H). ^{13}C NMR ($CDCl_3$): δ 145.8, 140.3, 138.9, 138.0, 136.4, 133.1, 132.2, 131.6, 130.0, 129.7, 127.8, 127.5, 125.8, 125.2, 124.2, 123.6, 123.4, 120.7, 120.0, 119.8, 119.7, 119.2, 113.2, 109.7, 108.3, 57.7, 28.2, 19.2.

(Benzotriazol-1-yl)(carbazol-9-yl)(triphenylsilyl)-methane (10f). ^{1}H NMR ($CDCl_3$): δ 8.08−7.89 (m, 4 H), 7.60−7.48 (m, 8 H), 7.46−7.30 (m, 4 H), 7.29−7.05 (m, 10 H), 6.98−6.92 (m, 2 H). ^{13}C NMR ($CDCl_3$): δ 145.9, 136.6, 132.9, 131.3, 130.2, 127.9, 127.8, 124.3, 120.0, 119.8, 109.7, 60.4.

Preparation of 2,4-Dinitrophenylhydrazones 11a−f. General Procedure. The appropriate intermediate product **10** (2 mmol) was added to a solution of 2,4-dinitrophenylhydrazine (2.4 mmol) in tetrahydrofuran (20 mL), water (10 mL), and concd H_2SO_4 (1 mL). The mixture was stirred at room temperature (for **10e,f**: 55−60 °C) for 24 h under nitrogen and extracted with chloroform (3 × 30 mL). The combined organic layers were washed with water (3 × 20 mL), dried over $MgSO_4$, and evaporated to give a residue which was triturated with chloroform (15 mL) and kept at −15 °C for 5 h. The crystallized carbazole was filtered off and the filtrate evaporated at reduced pressure to give the crude product which was recrystallized from ethanol to afford the pure product (Table 2).

2,4-Dinitrophenylhydrazone of Formyltrimethylsilane (11a). ^{1}H NMR ($CDCl_3$): δ 11.05 (s, 1 H), 9.07 (d, 1 H, J = 2.5 Hz), 8.29 (dd, 1 H, J_1 = 9.6 Hz and J_2 = 2.5 Hz), 8.02 (d, 1 H, J = 9.6 Hz), 7.84 (s, 1 H), 0.30 (s, 9 H). ^{13}C NMR ($CDCl_3$): δ 160.1, 144.7, 138.0, 129.7, 128.8, 123.2, 116.8, −2.5.

2,4-Dinitrophenylhydrazone of Formyl-*tert*-butyldimethylsilane (11b). ^{1}H NMR ($CDCl_3$): δ 11.09 (s, 1 H), 9.10 (d, 1 H, J = 2.4 Hz), 8.32 (dd, 1 H, J_1 = 9.5 Hz and J_2 = 2.4 Hz), 8.02 (d, 1 H, J = 9.5 Hz), 7.85 (s, 1 H), 1.00 (s, 9 H), 0.25 (s, 6 H). ^{13}C NMR ($CDCl_3$): δ 158.6, 144.7, 138.2, 129.8, 128.8, 123.2, 116.9, 26.3, 16.7, −6.7.

2,4-Dinitrophenylhydrazone of Formyltriisopropylsilane (11c). ^{1}H NMR ($CDCl_3$): δ 11.10 (s, 1 H), 9.13 (d, 1 H, J = 2.5 Hz), 8.35 (dd, 1 H, J_1 = 9.7 Hz and J_2 = 2.5 Hz), 8.00 (d, 1 H, J = 9.7 Hz), 7.84 (s, 1 H), 1.38−1.22 (m, 3 H), 1.46 (d, 18 H, J = 7.0 Hz). ^{13}C NMR ($CDCl_3$): δ 157.3, 144.7, 138.2, 130.0, 128.9, 123.4, 116.9, 18.5, 10.8.

2,4-Dinitrophenylhydrazone of Formyltriisobutylsilane (11d). ^{1}H NMR ($CDCl_3$): δ 11.06 (s, 1 H), 9.13 (d, 1 H, J = 2.5 Hz), 8.34 (dd, 1 H, J_1 = 9.5 Hz and J_2 = 2.5 Hz), 8.00 (d, 1 H, J = 9.5 Hz), 7.83 (s, 1 H), 1.84 (heptet, 3 H, J = 7.0 Hz), 0.98 (d, 18 H, J = 7.0 Hz), 0.83 (d, 6 H, J = 7.0 Hz). ^{13}C NMR ($CDCl_3$): δ 159.9, 144.8, 138.2, 130.0, 128.9, 123.4, 116.9, 26.5, 24.8, 23.4.

2,4-Dinitrophenylhydrazone of Formyl-*tert*-butyldiphenylsilane (11e). ^{1}H NMR ($CDCl_3$): δ 11.28 (s, 1 H), 9.11 (d, 1 H, J = 2.4 Hz), 8.29 (dd, 1 H, J_1 = 9.4 Hz and J_2 = 2.4 Hz), 8.13 (s, 1 H), 7.95 (d, 1 H, J = 9.4 Hz), 7.69 (d, 4 H, J = 5.9 Hz), 7.50−7.37 (m, 6 H), 1.23 (m, 9 H). ^{13}C NMR ($CDCl_3$): δ 155.5, 144.6, 138.4, 136.0, 132.0, 130.0, 129.9, 129.1, 127.9, 123.2, 117.0, 27.4, 18.6.

2,4-Dinitrophenylhydrazone of Formyltriphenylsilane (11f). ^{1}H NMR ($CDCl_3$): δ 11.29 (s, 1 H), 9.07 (d, 1 H, J = 2.5 Hz), 8.26 (dd, 1 H, J_1 = 2.5 Hz and J_2 = 1.0 Hz), 8.23 (d, 1 H, J = 1.0 Hz), 7.88 (d, 1 H, J = 9.5 Hz), 7.68−7.58 (m, 6 H), 7.57−7.36 (m, 9 H). ^{13}C NMR ($CDCl_3$): δ 154.8, 144.6, 138.6, 136.0, 131.7, 130.3, 129.9, 129.2, 128.2, 123.1, 117.1.

Preparation of (Triisopropylsilyl)vinyl 4-Nitrophenyl Ketone (13). Aqueous H_2SO_4 (5 mL H_2O and 0.5 mL of concd H_2SO_4) was added to a solution of **10c** (0.5 g, 1.1 mmol) in THF (10 mL). The mixture was stirred at room temperature under nitrogen for 24 h, and 4-nitroacetophenone (0.2 g, 1.2 mmol) was added. The pH of the mixture was immediately adjusted to 11−12 by using 20% NaOH at 0 °C. The mixture was allowed to stir at room temperature for 12 h and then extracted with Et_2O (3 × 20 mL). The combined organic layers were washed with 2 N NaOH (2 × 10 mL) and water (2 × 10 mL) and dried over $MgSO_4$. Evaporation of the solvent gave a residue which was triturated with chloroform (5 mL) and kept at −15 °C for 5 h. The crystallized carbazole was filtered off and the filtrate evaporated to give the crude product which was purified by column chromatography (silica gel, hexane/AcOEt = 10/1) to afford the pure product (0.11 g, 30%), mp 49−51 °C. ^{1}H NMR ($CDCl_3$): δ 8.34 (d, 2 H, J = 9.0 Hz), 8.08 (d, 2 H, J = 9.0 Hz), 7.33 (d, 1 H, J = 18.5 Hz), 7.28 (d, 1, H, J = 18.5 Hz), 1.30−1.18 (m, 3 H), 1.14 (d, 18 H, J = 6.7 Hz). ^{13}C NMR ($CDCl_3$): δ 188.6, 150.0, 148.6, 142.5, 139.5, 129.7, 123.8, 18.6, 10.8. Anal. Calcd for $C_{18}H_{27}NO_3Si$: C, 64.83; H, 8.16; N, 4.20. Found: C, 64.48; H, 8.13; N, 4.51.