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Active Cobalt Catalyst for the Cleavage of Benzyl Ether

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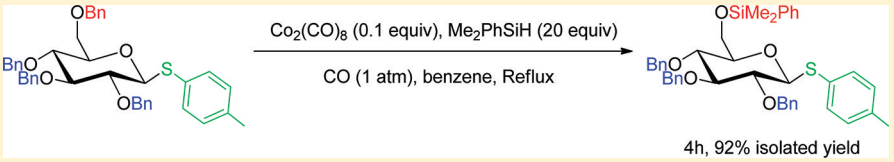
Supporting Information

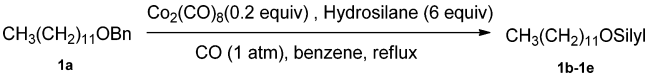


ABSTRACT: An improved method for the deprotection of benzyl ethers using a catalytic amount of $Co_2(CO)_8$ in the presence of Me_2PhSiH and CO (1 atm) is described. The deprotection reaction is compatible with double bond or sulfur-containing substrates. The method also tolerates other functional groups, such as Ac, Piv, and Bz, and shows potential selectivity in perbenzylated monosaccharides.

The protection and deprotection of hydroxyl groups are frequently needed in the synthesis of bioactive complex molecules. Among the many protective groups, benzyl ether is one of the most often used protecting groups because of its easy formation, inherent stability, and mild cleavage conditions.[1] A plethora of reagents and methods have been used to remove benzyl ethers, including catalytic hydrogenolysis,[2−6] reductive cleavage (lithium naphthalenide[7,8] and TIBAL,[9] etc.[10,11]), Lewis acid (TMSI[12] and $TiCl_4$,[13] etc.[14−16]), or oxidation-based cleavage (2,3-dichloro-5,6-dicyano-1,4-benzoquinone[17,18] and 4-acetamido-2,2,6,6-tetramethylpiperidine-1-oxoammonium tetrafluoroborate[19]). The triphenylphosphine hydrobromide[20] and the I_2/Et_3SiH system[21] were also used to cleave the benzyl ethers. However, most of the well-developed methods are incompatible with double and triple bonds or sulfur-containing substrates, which limit the application of benzyl ethers. Recently, our laboratory reported a highly efficient and thioglycoside compatible de-*O*-benzylation method based on the $Co_2(CO)_8$−CO−Et_3SiH system, in which greater than stoichiometric amounts of $Co_2(CO)_8$ (1.5 or 3 equiv) were used for the selective cleavage of primary benzyl ethers in complex saccharide.[22] However, the excess use of cobalt is not environmentally friendly, and the workup is tedious. Herein, we disclose an improved cobalt-catalyzed protocol for the efficient cleavage of benzyl ethers in a wide range of substrates.

Our previous study indicated that the electric and steric properties of substituents on the hydrosilane have great influence on the reaction because the hydrosilane is involved in the formation and activity of catalyst. It also participates in the oxidative addition to alkyl carbonyl cobalt complex and reduction of aldehyde. As a model study, benzyl ether **1a** was treated with $Co_2(CO)_8$ (0.2 equiv), various hydrosilanes (6.0 equiv), and CO (1 atm) under benzene reflux (Table 1). The bulky hydrosilanes, such as *t*-$BuMe_2SiH$, Ph_3SiH, and $(EtO)_3SiH$, did not produce any products, and Et_3SiH, which

Table 1. Screening of Hydrosilanes



entry	hydrosilane	product	time (h)	yield[a] (%)
1	$EtMe_2SiH$	$CH_3(CH_2)_{11}OSiMe_2Et$ (**1b**)	8	95
2	$PhMe_2SiH$	$CH_3(CH_2)_{11}OSiMe_2Ph$ (**1c**)	3	96
3	Ph_2MeSiH	$CH_3(CH_2)_{11}OSiMePh_2$ (**1d**)	48	25
4	Et_3SiH	$CH_3(CH_2)_{11}OSiEt_3$ (**1e**)	24	11
5	*t*-$BuMe_2SiH$		48	0
6	Ph_3SiH		48	0
7	$(EtO)_3SiH$		48	0

[a]Isolated yield.

was used in our previous report, provided a trace of desired product. In contrast, the less steric $EtMe_2SiH$ and Me_2PhSiH afforded the desired products in excellent yield. Therefore, Me_2PhSiH was chosen for further studies owing to its lower price and higher boiling point (156 °C compared with 46 °C for $EtMe_2SiH$).

The reaction conditions were further optimized (Table 2). The catalyst loading can be reduced to 0.1 equiv without compromising the product yield (entry 1). When the reaction was carried out with 0.05 or 0.01 equiv of $Co_2(CO)_8$, poor yields were obtained (entries 2 and 3). Decreasing the temperature also led to low yield (entry 4). In addition, when the reaction was carried out in DCM or 3 equiv of hydrosilane was used, the yields decreased to some extent (entries 5 and 6). Consequently, our optimal reaction conditions were 0.1 equiv of $Co_2(CO)_8$, 6 equiv of Me_2PhSiH, and CO (1 atm) in refluxing benzene.

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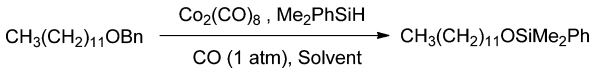
Table 2. Optimization Studies



entry	$Co_2(CO)_8$ (equiv)	Me_2PhSiH (equiv)	solvent	T (°C)	time (h)	yield[a] (%)
1	0.1	6	benzene	reflux	6	98
2	0.05	6	benzene	reflux	20	86
3	0.01	6	benzene	reflux	20	11
4	0.1	6	benzene	60	21	34
5	0.1	6	DCM	reflux	48	39
6	0.1	3	benzene	reflux	6.5	90

[a]Isolated yield.

Under the established optimal conditions, a wide spectrum of structurally diverse benzyl ethers were subjected to deprotection by this procedure and the results are summarized in Table 3. As shown, all of the primary benzyl ethers gave satisfactory results within a short reaction time (entries 1−5). However, the reaction rate for secondary benzyl ethers is slow, and a longer reaction time (10−72 h) is needed under standard conditions (entries 8−10). It should be emphasized that not only esters but also a double bond can survive under the deprotection conditions without any detected side products (entries 3−5, 7). In addition, the alcohol benzyl ether can be selectively cleaved in the presence of phenol benzyl ether (entry 6). The selectivity of this methodology was further illustrated in carbohydrate substrates (entries 11−14). The primary benzyl ethers can be selectively removed without affecting the secondary benzyl ethers by using 20 equiv of hydrosilane.

The proposed mechanism for the cleavage of benzyl ethers is shown in Scheme 1.[23] The actual active catalyst $Me_2PhSiCo(CO)_4$, generated in situ by mixing $Co_2(CO)_8$ with Me_2PhSiH, reacts initially with benzyl ether and generates the desired product and benzyl cobalt complex. After a series of transformations with the cobalt complex, the catalyst is regenerated. The well-known high affinity of the organosilyl group for oxygen could be the driving force for the catalytic cycle.

In conclusion, an efficient and selective method was developed for the efficient cleavage of benzyl ethers with cobalt catalyst, which is compatible with a wide range of substrates. The compatibility and selectivity of the method will present a valuable addition to the existing reagents. Studies to extend its application in the area of carbohydrate synthesis are underway.

EXPERIMENTAL SECTION

General Experimental Methods. All chemicals were purchased as reagent grade and used without further purification, unless otherwise noted. Dichloromethane was distilled over calcium hydride. Benzene was distilled from sodium. Analytical TLC was performed on silica gel 60 F_{254} precoated on glass plates, with detection by fluorescence and/or by staining with 5% concentrated sulfuric acid in EtOH. Column chromatography was performed employing silica gel (230−400 mesh). Optical rotations were recorded using an optical activity polarimeter. ^{1}H NMR spectra were recorded on advance spectrometers at 25 °C. Chemical shifts (in ppm) were referenced with tetramethylsilane (δ = 0 ppm) in deuterated chloroform, deuterated acetone, or deuterated benzene. ^{13}C NMR spectra were obtained by using the same NMR spectrometers and were calibrated with $CDCl_3$ (δ = 77.00 ppm), $(CD_3)_2CO$ (δ = 29.84, 206.26 ppm), or C_6D_6 (δ = 128.00 ppm). High-resolution mass spectrometry was performed on a mass spectrometer.

General Procedures for the Deprotection of Benzyl Ethers. $Co_2(CO)_8$ (0.1 equiv or 0.2 equiv) was added to a flask under CO atmosphere. Me_2PhSiH (6 equiv or 20 equiv) was then added, and the mixture was stirred for 30 min at room temperature. A solution of benzyl ethers or perbenzylated saccharides in anhydrous benzene (1 mmol/5 mL) was degassed and added using a syringe. The mixture was heated to reflux in an oil bath. The reaction was monitored by TLC. After the disappearance of starting materials, the cobalt complex was precipitated by the dropwise addition of pyridine and subsequent bubbling of air through the solution for 20 min. The content of the flask was filtered through 5 cm of silica gel and eluted with chloroform. The filtrate was evaporated, and the residue was subjected to flash chromatography.

(Dodecyloxy)(ethyl)dimethylsilane (1b): colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.50 (t, 2H, J = 6.7 Hz), 1.40−1.50 (m, 2H), 1.15−1.28 (m, 18H), 0.88 (t, 3H, J = 7.9 Hz), 0.81 (t, 3H, J = 6.8 Hz), 0.50 (q, 2H, J = 7.9 Hz), 0.01 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 62.8, 32.8, 31.9, 29.7, 29.6, 29.6, 29.5, 29.4, 25.8, 22.7, 14.1, 8.0, 6.7, −2.7; HRMS (ESI) calcd for $C_{16}H_{36}OSi$ $[M + H]^+$ 273.2614, found 273.2608.

(Dodecyloxy)dimethyl(phenyl)silane (1c): colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.42−7.54 (m, 2H), 7.22−7.34 (m, 3H), 3.51 (t, 2H, J = 6.7 Hz), 1.40−1.50 (m, 2H), 1.10−1.30 (m, 18H), 0.81 (t, 3H, J = 7.0 Hz), 0.30 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 138.2, 133.5, 129.5, 127.8, 63.2, 32.6, 31.9, 29.6, 29.4, 29.3, 25.8, 22.7, 14.1, −1.8; HRMS (ESI) calcd for $C_{20}H_{36}OSi$ $[M + H]^+$ 321.2614, found 321.2614.

(Dodecyloxy)(methyl)diphenylsilane (1d): colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.48−7.56 (m, 4H), 7.26−7.36 (m, 6H), 3.61 (t, 2H, J = 6.7 Hz), 1.49 (m, 2H), 1.10−1.30 (m, 18H), 0.80 (t, 3H, J = 6.8 Hz), 0.56 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 136.3, 134.3, 129.7, 127.8, 63.6, 32.6, 31.9, 29.7, 29.6, 29.6, 29.4, 29.4, 25.8, 22.7, 14.1, −3.0; HRMS (ESI) calcd for $C_{25}H_{38}OSi$ $[M + H]^+$ 383.2770, found 383.2766.

(Dodecyloxy)triethylsilane (1e): colorless oil; ^{1}H NMR (400 MHz, $(CD_3)_2CO$) δ 3.50 (t, 2H, J = 6.4 Hz), 1.38 (m, 2H), 1.30−1.10 (m, 18H), 0.83 (t, 9H, J = 7.9 Hz), 0.75 (t, 3H, J = 7.0 Hz), 0.47 (q, 6H, J = 7.9 Hz); ^{13}C NMR (100 MHz, $(CD_3)_2CO$) δ 63.3, 33.7, 32.7, 30.4, 30.4, 30.2, 30.1, 26.6, 23.4, 14.4, 7.1, 5.1; HRMS (ESI) calcd for $C_{18}H_{40}OSi$ $[M + H]^+$ 301.2927, found 301.2920.

Dimethyl(phenyl)(3-phenylpropoxy)silane (2b): colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.42−7.52 (m, 2H), 7.2−7.3 (m, 3H), 7.08−7.18 (m, 2H), 6.98−7.08 (m, 3H), 3.52 (t, 2H, J = 6.3 Hz), 2.55 (t, 2H, J = 7.9 Hz), 1.74 (m, 2H), 0.28 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 142.0, 138.0, 133.4, 129.5, 128.4, 128.2, 127.8, 125.6, 62.3, 34.1, 32.0, −1.8; HRMS (ESI) calcd for $C_{17}H_{22}OSi$ $[M + H]^+$ 271.1518, found 271.1517.

(4-Methoxyphenethoxy)dimethyl(phenyl)silane (3b): colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40−7.47 (m, 2H), 7.23−7.34 (m, 3H), 6.99 (d, 2H, J = 8.5 Hz), 6.73 (d, 2H, J = 8.5 Hz), 3.70 (s, 3H), 3.67 (t, 2H, J = 7.3 Hz), 2.69 (t, 2H, J = 7.2 Hz), 0.25 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 158.1, 137.8, 133.4, 131.0, 130.0, 129.5, 127.8, 113.7, 64.5, 55.2, 38.4, −1.9; HRMS (ESI) calcd for $C_{17}H_{22}O_2Si$ $[M + Na]^+$ 309.1287, found 309.1288.

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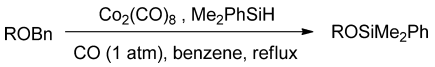
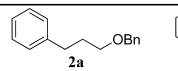
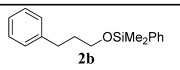
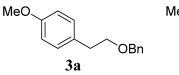
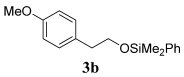
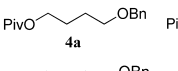
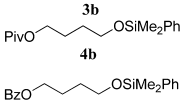
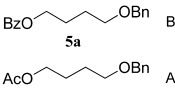
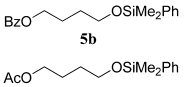
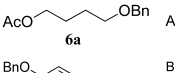
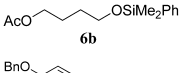
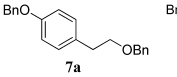
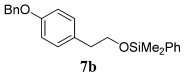
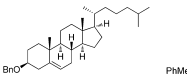
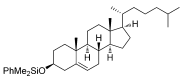
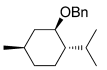
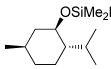
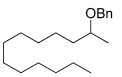
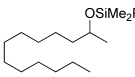
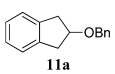
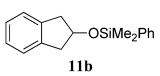
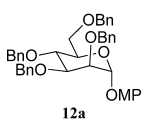
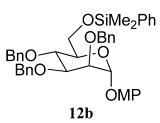
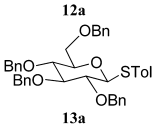
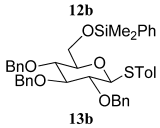
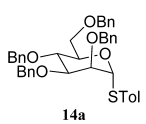
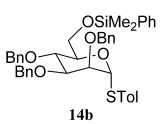
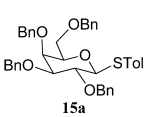
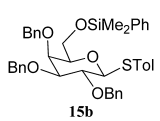
Table 3. Screening of Substrates



Entry	Reactant	Product	$Co_2(CO)_8$ (equiv)	Me_2PhSiH (equiv)	Time (h)	Yield (%)[a]
1	 **2a**	 **2b**	0.1	6	6	94
2	 **3a**	 **3b**	0.1	6	7	98
3	 **4a**	 **4b**	0.1	6	7	72
4	 **5a**	 **5b**	0.1	6	4	75
5	 **6a**	 **6b**	0.1	6	5	63
6	 **7a**	 **7b**	0.1 0.05	6 6	12 7	60 72[b]
7	 **8a**	 **8b**	0.2	6	50	76
8	 **9a**	 **9b**	0.2	6	72	85
9	 **10a**	 **10b**	0.2	6	10	82
10	 **11a**	 **11b**	0.2	6	24	61
11	 **12a**	 **12b**	0.1[c]	20[d]	6	68
12	 **13a**	 **13b**	0.1	20	4	92
13	 **14a**	 **14b**	0.1	20	2	74
14	 **15a**	 **15b**	0.1	20	5	76

[a]Isolated yield after chromatography on SiO_2. [b]Toluene, reflux. [c]The yield could be increased to 81.6% when 0.2 equiv of $Co_2(CO)_8$ was used. [d]The yield would be decreased to 15.8% when the amount of Me_2PhSiH was reduced to 10 equiv in 24 h.

4-(Benzyloxy)butyl pivalate (4a): colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.17−7.31 (m, 5H), 4.44 (s, 2H), 4.00 (t, 2H, J = 6.3 Hz), 3.43 (t, 2H, J = 6.2 Hz), 1.64 (m, 4H), 1.12 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 178.6, 138.5, 128.4, 127.6, 127.6, 72.9, 69.8, 64.2, 38.7, 27.2, 26.3, 25.5; HRMS (ESI) calcd for $C_{16}H_{24}O_3$ $[M + Na]^+$ 287.1623, found 287.1615.

4-((Dimethyl(phenyl)silyl)oxy)butyl pivalate (4b): colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46−7.52 (m, 2H), 7.26−7.34 (m, 3H), 3.96 (t, 2H, J = 6.3 Hz), 3.54 (t, 2H, J = 6.2 Hz), 1.46−1.65 (m, 4H), 1.11 (s, 9H), 0.30 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 178.5, 137.9, 133.4, 129.6, 127.8, 64.1, 62.5, 38.7, 29.1, 27.2, 25.2, −1.8; HRMS (ESI) calcd for $C_{17}H_{28}O_3Si$ $[M + Na]^+$ 331.1705, found 331.1702.

4-((Dimethyl(phenyl)silyl)oxy)butyl benzoate (5b): colorless oil; ^{1}H NMR (400 MHz, $(CD_3)_2CO$) δ 7.99−8.05 (m, 2H), 7.58−7.66 (m, 3H), 7.48−7.54 (m, 2H), 7.34−7.41 (m, 3H), 4.32 (t, 2H, J = 6.4 Hz), 3.72 (t, 2H, J = 6.2 Hz), 1.76−1.89 (m, 2H), 1.65−1.73 (m, 2H), 0.36 (s, 6H); ^{13}C NMR (100 MHz, $(CD_3)_2CO$) δ 166.7, 138.9, 134.2, 133.8, 131.5, 130.4, 130.1, 129.4, 128.6, 65.4, 63.1, 29.9, 26.1,

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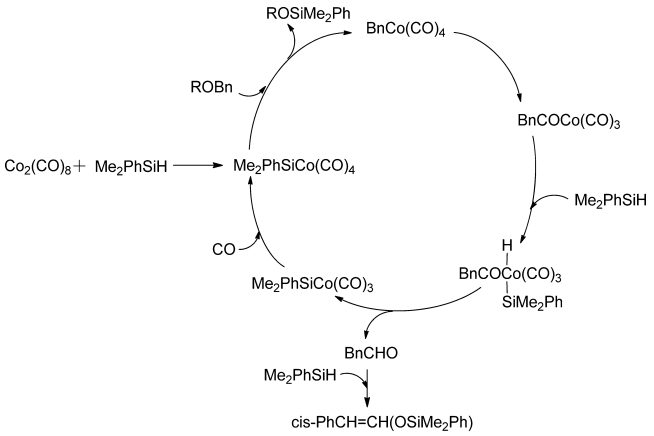
Scheme 1. Proposed Mechanism



−1.6; HRMS (ESI) calcd for $C_{19}H_{24}O_3Si$ [M + Na]$^+$ 351.1392, found 351.1390.

4-((Dimethyl(phenyl)silyl)oxy)butyl acetate (6b): colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.54−7.60 (m, 2H), 7.35−7.42 (m, 3H), 4.04 (t, 2H, J = 6.5 Hz), 3.61 (t, 2H, J = 6.2 Hz), 2.02 (s, 3H), 1.62 (m, 4H), 0.37 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.1, 137.8, 133.4, 129.6, 127.8, 64.3, 62.4, 29.0, 25.1, 21.0, −1.9; HRMS (ESI) calcd for $C_{14}H_{22}O_3Si$ [M + Na]$^+$ 289.1236; found 289.1231.

(4-(Benzyloxy)phenethoxy)dimethyl(phenyl)silane (7b): colorless oil; ^{1}H NMR (400 MHz, $(CD_3)_2CO$) δ 7.27−7.57 (m, 10H), 7.12 (d, 2H, J = 8.4 Hz), 6.92 (d, 2H, J = 8.4 Hz), 5.08 (s, 2H), 3.78 (t, 2H, J = 7 Hz), 2.75 (t, 2H, J = 6.8 Hz), 0.30 (s, 6H); ^{13}C NMR (100 MHz, $(CD_3)_2CO$) δ 158.3, 138.9, 138.6, 134.2, 132.3, 130.9, 130.3, 129.2, 128.6, 128.5, 128.3, 115.5, 70.4, 65.0, 39.1, −1.6; HRMS (ESI) calcd for $C_{23}H_{26}O_2Si$ [M + Na]$^+$ 385.1600, found 385.1599.

(((3*S*,8*S*,9*S*,10*R*,13*R*,14*S*,17*R*)-10,13-Dimethyl-17-((*R*)-6-methylheptan-2-yl)-2,3,4,7,8,9,10,11,12,13,14,15,16,17-tetradecahydro-1*H*-cyclopenta[*a*]phenanthren-3-yl)oxy)dimethyl(phenyl)silane (8b): colorless oil; $[\alpha]^{25}_D$ −29.9 (*c* 1.1, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.48−7.54 (m, 2H), 7.26−7.32 (m, 3H), 5.15−5.21 (m, 1H), 3.44 (m, 1H), 2.24 (m, 1H), 2.04−2.12 (m, 1H), 1.82−1.97 (m, 2H), 0.7−1.80 (m, 36H), 0.59 (s, 3H), 0.31 (s, 3H), 0.31 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ141.3, 138.5, 133.4, 129.4, 127.7, 121.4, 72.7, 56.8, 56.1, 50.2, 42.6, 42.3, 39.8, 39.5, 37.3, 36.5, 36.2, 35.8, 31.9, 31.9, 29.7, 28.2, 28.0, 24.3, 23.8, 22.8, 22.6, 21.0, 19.4, 18.7, 11.8, −0.1, −1.1; HRMS (ESI) calcd for $C_{35}H_{56}OSi$ [M + Na]$^+$ 543.3998, found 543.4002.

(((1*R*,2*S*,5*R*)-2-Isopropyl-5-methylcyclohexyl)oxy)dimethyl(phenyl)silane (9b): colorless oil; $[\alpha]^{25}_D$ −37.2 (*c* 1.1, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.56−7.64 (m, 2H), 7.34−7.41 (m, 3H), 3.42 (m, 1H), 2.12−2.25 (m, 1H), 1.78−1.88 (m, 1H), 1.52−1.65 (m, 2H), 1.25−1.38 (m, 1H), 1.13−1.22 (m, 1H), 1.02 (m, 1H), 0.75−0.95 (m, 8H), 0.62 (d, 3H, J = 6.9 Hz), 0.39 (s, 3H), 0.39 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ138.6, 133.5, 129.4, 127.7, 72.8, 50.1, 45.4, 34.5, 31.6, 25.2, 22.8, 22.3, 21.3, 15.7, −0.7, −0.9; HRMS (ESI) calcd for $C_{18}H_{30}OSi$ [M + Na]$^+$ 313.1964, found 313.1961.

((Tridecan-2-yloxy)methyl)benzene (10a): colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.13−7.32 (m, 5H), 4.34−4.51 (m, 2H), 3.36−3.47 (m, 1H), 1.45−1.57 (m, 1H), 1.06−1.42 (m, 22H), 0.80 (t, 3H, J = 6.7 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 139.2, 128.2, 127.6, 127.3, 74.9, 70.2, 36.7, 31.9, 29.7, 29.7, 29.6, 29.3, 25.5, 22.7, 19.6, 14.1; HRMS (ESI) calcd for $C_{20}H_{34}O$ [M + Na]$^+$ 313.2507, found 313.2503.

Dimethyl(phenyl)(tridecan-2-yloxy)silane (10b): colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.49−7.54 (m, 2H), 7.25−7.33 (m, 3H), 3.71 (m, 1H), 1.06−1.44 (m, 20H), 1.02 (d, 3H, J = 6.0 Hz), 0.81 (t, 3H, J = 6.8 Hz), 0.30 (s, 3H), 0.30 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 138.6, 133.5, 129.4, 127.7, 69.0, 39.5, 31.9, 29.7, 29.6, 29.6, 29.4, 25.8, 23.7, 22.7, 14.1, −1.0, −1.1; HRMS (ESI) calcd for $C_{21}H_{38}OSi$ [M + Na]$^+$ 357.2590, found 357.2583.

((2,3-Dihydro-1*H*-inden-2-yl)oxy)dimethyl(phenyl)silane (11b): colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.43−7.55 (m, 2H), 7.23−7.34 (m, 3H), 7.01−7.10 (m, 4H), 4.56 (m, 1H), 2.97 (dd, 2H, J = 6.6, 15.7 Hz), 2.82 (dd, 2H, J = 5.6, 15.7 Hz), 0.32 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ141.0, 138.1, 133.5, 129.6, 127.8, 126.4, 124.6, 74.0, 42.3, −1.2; HRMS (ESI) calcd for $C_{17}H_{20}OSi$ [M + Na]$^+$ 291.1181, found 291.1172.

***p*-Methoxyphenyl 2,3,4-tri-*O*-benzyl-6-*O*-dimethylphenylsilyl-α-D-mannopyranoside (12b):** colorless oil; $[\alpha]^{25}_D$ +42.7 (*c* 0.8, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.45−7.52 (m, 2H), 7.11−7.33 (m, 18H), 6.83−6.87 (m, 2H), 6.66−6.70 (m, 2H), 5.34 (d, 1H, J = 1.8 Hz), 4.82 (d, 1H, J = 10.9 Hz), 4.71 (d, 1H, J = 12.4 Hz), 4.65 (d, 1H, J = 12.4 Hz), 4.61 (d, 2H, J = 2.0 Hz), 4.49 (d, 1H, J = 10.9 Hz), 4.01 (dd, 1H, J = 3.0, 9.3 Hz), 3.94 (t, 1H, J = 9.4 Hz), 3.86 (dd, 1H, J = 2.2, 2.8 Hz), 3.79 (dd, 1H, J = 4.9, 11.4 Hz), 3.74 (dd, 1H, J = 2.0, 11.3 Hz), 3.64−3.70 (m, 4H), 0.27 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.9, 150.4, 138.6, 138.5, 138.3, 137.9, 133.6, 129.4, 128.3, 128.3, 127.8, 127.7, 127.7, 127.7, 127.6, 127.6, 127.5, 118.0, 114.4, 97.1, 79.9, 74.9, 74.9, 74.6, 73.4, 72.6, 72.3, 62.4, 55.6, −1.5, −1.7; HRMS (ESI) calcd for $C_{42}H_{46}O_7Si$ [M + Na]$^+$ 713.2905, found 713.2886.

***p*-Methylphenyl 2,3,4-tri-*O*-benzyl-6-*O*-dimethylphenylsilyl-1-thio-β-D-glucopyranoside (13b):** colorless oil; $[\alpha]^{25}_D$ −4.4 (*c* 1.8, $CHCl_3$); ^{1}H NMR (400 MHz, C_6D_6) δ 7.34−7.41 (m, 4H), 7.14−7.16 (m, 2H), 6.77−7.00 (m, 16H), 6.60 (d, 2H, J = 7.9 Hz), 4.68 (d, 1H, J = 10.7 Hz), 4.60 (d, 1H, J = 11.3 Hz), 4.53 (t, 2H, J = 11.8 Hz), 4.43 (d, 1H, J = 10.8 Hz), 4.32−4.35 (m, 2H), 3.57 (dd, 1H, J = 1.9, 11.4 Hz), 3.52 (dd, 1H, J = 3.8, 11.4 Hz), 3.43 (t, 1H, J = 9.3 Hz), 3.32 (t, 1H, J = 8.7 Hz), 3.22 (t, 1H, J = 9.1 Hz), 2.82−2.86 (m, 1H), 1.73 (s, 3H), 0.15 (s, 3H), 0.15 (s, 3H); ^{13}C NMR (100 MHz, C_6D_6) δ 139.4, 139.2, 139.2, 138.2, 137.4, 134.1, 132.8, 131.4, 129.9, 129.8, 128.5, 128.2, 128.12, 127.9, 127.9, 127.7, 127.6, 88.4, 87.0, 81.5, 80.2, 77.6, 75.5, 75.4, 74.9, 62.6, 21.0, −1.3; HRMS (ESI) calcd for $C_{42}H_{46}O_5SSi$ [M + Na]$^+$ 713.2727, found 713.2719.

***p*-Methylphenyl 2,3,4-tri-*O*-benzyl-6-*O*-dimethylphenylsilyl-1-thio-α-D-mannopyranoside (14b):** colorless oil; $[\alpha]^{25}_D$ +61.1 (c 1.1, $CHCl_3$). ^{1}H NMR (400 MHz, C_6D_6) δ 7.32−7.34 (m, 2H), 7.26−7.28 (m, 2H), 6.96−7.03 (m, 6H), 6.75−6.93 (m, 12H), 6.62 (d, 2H, J = 7.9 Hz), 5.45 (d, 1H, J = 1.0 Hz), 4.69 (d, 1H, J = 11.4 Hz), 4.31 (d, 1H, J = 11.4 Hz), 4.19−4.23 (m, 1H), 4.15 (d, 1H, J = 12.2 Hz), 4.12 (s, 2H), 4.07 (d, 1H, J = 12.2 Hz), 4.01 (t, 1H, J = 9.5 Hz), 3.75−3.79 (m, 2H), 3.72 (dd, 1H, J = 4.9, 11.3 Hz), 3.67 (dd, 1H, J = 2.0, 11.3 Hz), 1.74 (s, 3H), 0.08 (s, 3H), 0.07 (s, 3H); ^{13}C NMR (100 MHz, C_6D_6) δ 139.5, 139.0, 138.8, 138.4, 137.5, 134.0, 132.6, 131.8, 130.0, 129.6, 128.5, 128.5, 128.4, 128.1, 127.9, 127.5, 86.7, 81.1, 77.4, 75.3, 75.1, 74.6, 72.2, 72.1, 63.0, 21.0, −1.2, −1.5; HRMS (ESI) calcd for $C_{42}H_{46}O_5SSi$ [M + NH_4]$^+$ 708.3174, found 708.3166.

***p*-Methylphenyl 2,3,4-tri-*O*-benzyl-6-*O*-dimethylphenylsilyl-1-thio-β-D-galactopyranoside (15b):** colorless oil; $[\alpha]^{25}_D$ −5.6 (*c* 1.4, $CHCl_3$); ^{1}H NMR (400 MHz, C_6D_6) δ 7.38−7.41 (m, 2H), 7.26−7.29 (m, 2H), 7.13−7.15 (m, 2H), 7.03−7.05 (m, 2H), 6.78−6.97 (m, 14H), 6.53 (d, 2H, J = 8.0 Hz), 4.74 (d, 1H, J = 11.4 Hz), 4.58 (d, 1H, J = 10.8 Hz), 4.40 (d, 1H, J = 10.8 Hz), 4.31 (d, 1H, J = 9.6 Hz), 4.28 (d, 1H, J = 11.4 Hz), 4.19 (d, 1H, J = 11.9 Hz), 4.13 (d, 1H, J = 11.9 Hz), 3.86 (t, 1H, J = 9.4 Hz), 3.62 (d, 2H, J = 6.6 Hz), 3.58 (d, 1H, J = 2.3 Hz), 3.04−3.07 (m, 2H), 1.71 (s, 3H), 0.05 (s, 3H), 0.04 (s, 3H); ^{13}C NMR (100 MHz, C_6D_6) δ 139.5, 139.1, 137.9, 137.0, 133.8, 132.6, 131.3, 130.0, 129.8, 128.6, 128.4, 128.4, 128.1, 127.9, 127.7, 127.6, 127.5, 88.3, 84.8, 79.1, 77.7, 75.5, 74.8, 74.1, 72.8, 62.2, 21.0, −1.8, −1.9; HRMS (ESI) calcd for $C_{42}H_{46}O_5SSi$ [M + Na]$^+$ 713.2727, found 713.2728.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

General procedures and characterization data (^{1}H and ^{13}C NMR spectra). This material is available free of charge via the Internet at http://pubs.acs.org.

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