Regioselective Silane-Terminated Intramolecular Heck Reaction with Alkenyl Triflates and Alkenyl Iodides

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Dedicated to Professor Bernd Giese on the occasion of his 60th birthday

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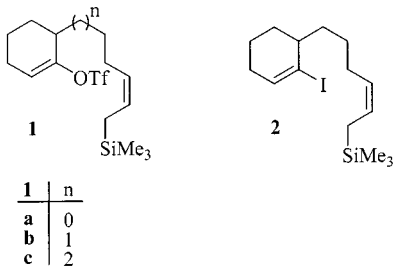
One of the main problems of the Heck reaction using acyclic substrates which lead to Pd intermediates with β- and β'-hydrogens is the lack of selectivity in the formation of the double bond as the last step of the catalytic cycle. The use of allylsilanes as the alkene moiety permits control of the elimination step. Thus, the Pd^0-catalysed reaction of **1a–c** and **2** leads exclusively to the corresponding bicyclic compounds **11a–c**. In contrast, reaction of **7** yields a mixture of **12a**, (*E*)-**12b** and (*Z*)-**12b**.

Introduction

The palladium-catalysed arylation and alkenylation of alkenes, known as the Heck reaction,[1] is nowadays one of the most important C−C bond forming transformations and has been used in numerous syntheses of natural products.[2] The broad application of this reaction is due to its excellent functional group tolerance and the possibility of using chiral ligands.[3] The Heck reaction is not only an excellent method for the formation of substituted carbocyclic systems, but also for heterocyclic ones. However, one of the main disadvantages is the low selectivity of the β-hydride elimination to form the double bond as the last step in the catalytic cycle. Acyclic substrates which form Pd-intermediates with β- and β'-hydrogens always give mixtures of double bond isomers. Another problem is the readdition of the eliminated X−PdL_n−H species to the formed alkene moiety, which can also lead to a mixture of double bond isomers. In previous papers we have shown that these shortcomings can be overcome in intramolecular Heck reactions of iodoarenes by using allylsilanes.[4,5] This permitted the selective formation of tertiary stereogenic centers starting from acyclic alkenes. In this paper we report on the extension of the silane-terminated intramolecular Heck reaction methodology to alkenyl triflates such as **1a−c** and alkenyl iodides containing a (*Z*)-allylsilane moiety, such as **2** (Scheme 1).

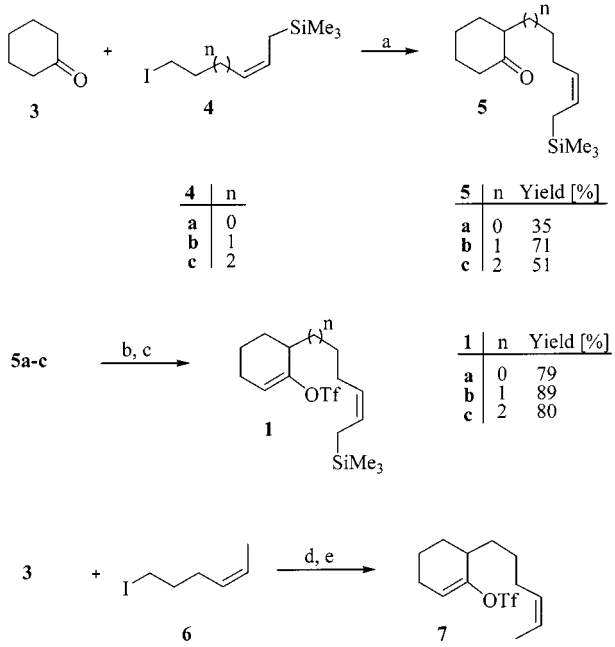


1	n
a	0
b	1
c	2

Scheme 1. Substrates for the allylsilane-terminated Heck reaction

Results and Discussion

The synthesis of the alkenyl triflates **1a−c** was performed by alkylation of cyclohexanone **3** with the (*Z*)-iodides **4a−c** in 35−71% yield, followed by the regioselective conversion into the triflates using LDA and Tf_2NPh in 79−89% yield (Scheme 2).[6] We also prepared the alkenyl triflate **7** without a trimethylsilyl group from **6** by following the same strategy, in 46% overall yield. **7** was used for comparison to



4	n
a	0
b	1
c	2

5	n	Yield [%]
a	0	35
b	1	71
c	2	51

1	n	Yield [%]
a	0	79
b	1	89
c	2	80

Scheme 2. Synthesis of substrates for the Heck reaction; reagents and conditions: a) $KN(SiMe_3)_2$, THF, −78 °C→room temp.; b) LDA, THF, −78 °C, 3 h; c) Tf_2NPh, −78 °C→0 °C, 15 h; d) $KN(SiMe_3)_2$, THF, −78 °C→room temp., 58%; e) LDA, THF, −78 °C, 3 h, Tf_2NPh, −78 °C→0 °C, 79%

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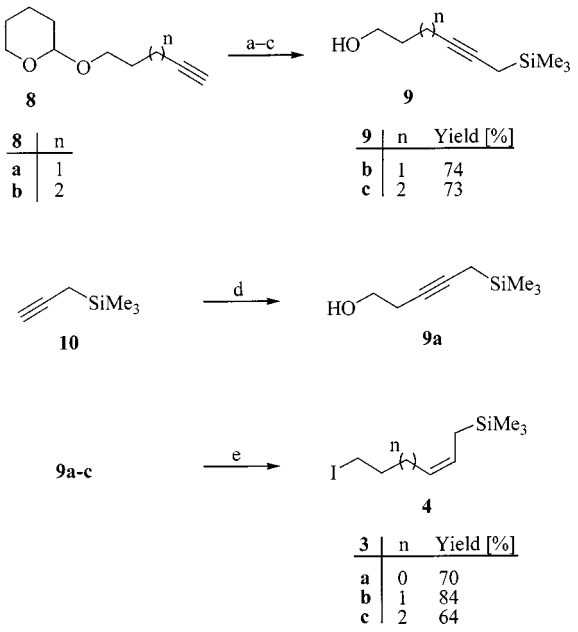
show the importance of the allylsilane moiety for the control of the X−PdL$_n$−H elimination.

The (*Z*)-iodides **4b−c** were prepared from the protected alkynes **8b−c** by deprotonation with *n*BuLi and alkylation with Me_3SiCH_2I, acidic deprotection, (*Z*)-selective reduction of the triple bond with P_2−Ni[7] and iodination following the *Appel*[8] procedure, in 62% (**4b**) and 47% yield (**4c**) over four steps (Scheme 3). The iodide **4a** was prepared differently, starting from the alkyne **10** and oxirane. Subsequent P_2−Ni reduction and *Appel*-iodination gave **4a** in 48% yield over four steps.[4c]



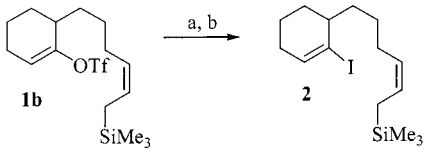
8	n
a	1
b	2

9	n	Yield [%]
b	1	74
c	2	73

3	n	Yield [%]
a	0	70
b	1	84
c	2	64

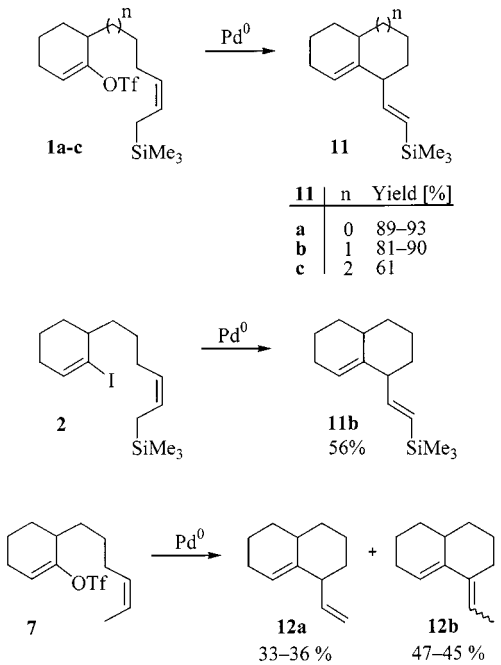
Scheme 3. Synthesis of allylsilanes **4**; reagents and conditions: a) *n*BuLi, THF, −30 °C→0 °C; b) Me_3SiCH_2I, 60−65 °C, 16 h; c) cat. H_2SO_4, MeOH, 16 h; d) *n*BuLi, toluene, −45 °C, Et_2AlCl (1.3 equiv.), oxirane (1.3 equiv.), 69%; e) P_2−Ni/H_2, EtOH; f) PPh_3, imidazole, I_2, Et_2O/MeCN

The synthesis of the alkenyl iodide **2** was accomplished by a palladium-catalysed reaction of the alkenyl triflate **1b** with hexamethyldistannane followed by iodination with an excess of iodine in 67% overall yield (Scheme 4).[9]



Scheme 4. Synthesis of vinyl iodide **2**; reagents and conditions: a) $Me_3Sn-SnMe_3$, 2 mol-% [$Pd(PPh_3)_4$], LiCl, THF, 60 °C, 16 h; b) I_2 (2.0 equiv.), room temp., 20 h, 67%

The silane-terminated Heck reaction of the alkenyl triflate **1a** (Scheme 5) was best accomplished with a catalyst system containing 10 mol-% of $Pd(OAc)_2$, 20 mol-% PPh_3 and two equivalents of NEt_3 in toluene at 80 °C, to give exclusively the trimethylsilyl-substituted hexahydroindene **11a** in 93% yield with a *trans*/*cis* diastereoselectivity of 90:10 (Table 1, entry 1). The use of THF as solvent gave **11a** in 89% yield with a *trans*/*cis* diastereoselectivity of 80:20 (Table 1, entry 2). The best result in the cyclisation of substrate **1b** was obtained by using a catalyst system of 10 mol-% of $Pd(OAc)_2$, 20 mol-% PPh_3 and 2 equivalents of NEt_3 in toluene at 75 °C. The octahydronaphthalene **11b** was formed in 2 h in 90% yield and with a *trans*/*cis* diastereoselectivity of 60:40 (Table 1, entry 3). The use of THF instead of toluene led to **11b** in 81% yield with a diastereoselectivity of 68:32 (*trans*:*cis*) (Table 1, entry 4). Surprisingly, the $Pd(OAc)_2/PPh_3/NEt_3$ catalyst system was not suitable for the cyclisation of the allylsilane **1c**; only traces of the bicycloundecene **11c** were detected. The optimised procedure for this system uses 6 mol-% $Pd_2(dba)_3{\cdot}CHCl_3$ (dba = dibenzylideneacetone), 12 mol-% dppb [dppb = 1,4-bis(diphenylphosphano)butane] and 10 equivalents of KOAc in DMF. The bicycloundecene **11c** was exclusively obtained in 61% yield after 16 h at 90 °C, but with a low *trans*/*cis* diastereoselectivity of 53:47 (Table 1, entry 5). The silane-terminated Heck cyclisation of the alkenyl iodide **2** was best accomplished with a catalyst system containing 6 mol-% $Pd_2(dba)_3{\cdot}CHCl_3$, 12 mol-% dppb and 10 equivalents of KOAc in DMF at 80 °C (Scheme 5). The octahydronaphthalene was formed after 2 h in 56% yield as the sole product with a *trans*/*cis* diastereoselectivity of 96:4 (Table 1, entry 6). The use of a silver salt instead of KOAc was unfavourable for the regio- and stereoselectivity of the reaction. Thus, the addition of an equimolar amount of Ag_3PO_4 gave **11b** in 57% yield with a *trans*/*cis* diastereoselectivity of 69:31. In addition, about 9% of the unwanted double bond isomers were formed. As found for the reaction of **1c**, almost no transformation was observed when the catalyst system $Pd(OAc)_2/PPh_3/NEt_3$ in toluene was used.



11	n	Yield [%]
a	0	89–93
b	1	81–90
c	2	61

Scheme 5. Heck reactions of **1**, **2** and **7**

To show the significance of the presence of a trimethylsilyl moiety in the substrates for regioselective β-hydride elimination, a Heck reaction of **7** was performed under the con-

Table 1. Intramolecular Heck reactions with alkenyl triflates and alkenyl iodides

Entry	Substrate	Product	Conditions	Temp. [°C]	Time [h]	Yield [%](Diastereoselec.)[a]
1	**1a**	**11a**	$Pd(OAc)_2/PPh_3/NEt_3$/ toluene	80	3	93 (90:10)
2	**1a**	**11a**	$Pd(OAc)_2/PPh_3/NEt_3$/ THF	65	3	89 (80:20)
3	**1b**	**11b**	$Pd(OAc)_2/PPh_3/NEt_3$/ toluene	75	2	90 (60:40)
4	**1b**	**11b**	$Pd(OAc)_2/PPh_3/NEt_3$/ THF	50	3	81 (68:32)
5	**1c**	**11c**	$Pd_2(dba)_3{\cdot}CHCl_3$/dppb/ KOAc/DMF	90	16	61 (53:47)
6	**2**	**11b**	$Pd_2(dba)_3{\cdot}CHCl_3$/dppb/ KOAc/DMF	80	2	56 (96:4)
7	**7**	**12a** **12b**	$Pd(OAc)_2/PPh_3/NEt_3$/ toluene	70	4	**12a**, 33 **12b**, 47
8	**7**	**12a** **12b**	$Pd(OAc)_2/PPh_3/NEt_3$/ THF	65	4	**12a**, 36 **12b**, 45

[a] Diastereoselectivity determined by GC.

ditions optimised for compound **1b** (Scheme 5). With a catalyst system containing 10 mol-% of $Pd(OAc)_2$, 20 mol-% PPh_3 and 2 equivalents of NEt_3 in toluene at 70 °C, an inseparable mixture of the double bond isomers **12a** (33%), (*E*)-**12b** and (*Z*)-**12b** (47% together) was obtained. A similar result was found using THF at 65 °C (Table 1, entry 7−8).

The results of the Heck reactions of **1** and **2** with an allylsilane moiety as the terminating group, compared with those of **7** with an alkene, clearly demonstrate the importance of the trimethylsilyl group for the regioselective elimination of the X−PdL_n−H in the intermediate Pd-complex. In the reactions of **1a−c** and **2**, products **11a−c** with an (*E*)-vinylsilane moiety were formed almost exclusively. In some cases, small amounts (less than 5%) of the products with a vinyl group were detected, but there was no trace of products of type **12b** under the normal conditions. In our former investigations employing aryl iodides we have shown that, in the absence of a silver salt, the product with a vinyl group is formed almost exclusively, whereas in the presence of a silver salt the product with an (*E*)-trimethylsilylvinyl group is produced. We explained the formation of the product with a trimethylsilylvinyl group by the intermediate creation of a Pd^+ species which would facilitate a fast PdL_nH^+ elimination of the more acidic hydrogen in the *α*-position to the trimethylsilyl group. This would correspond with the reaction of **1,** since the Pd−OTf bond is rather weak and could dissociate to form a Pd^+ species. On the other hand, employing **2** with a vinyl iodide moiety should result in the formation of the vinyl-substituted compound. However, since in general the alkenyl−PdL_n−X species are more reactive than their aryl−PdL_n−X counterparts, we have to assume in this case that the PdL_n−H elimination is again preferred over a formal $IPdL_2SiMe_3$ elimination, which probably proceeds by means of the intermediate formation of a *β*-trimethylsilyl carbocation.

The structures of the new compounds were mainly determined by ^{1}H NMR spectroscopy. The *Z* configuration of the alkene moiety in substrates **1**, **2** and **7** was deduced from the coupling constants of J = 10−10.5 Hz. The two hydrogens of the vinylsilanyl moiety in the products **11a−c** resonate at δ = 5.52−5.62 as a doublet of doublets, with J = 18.0−18.5 and 1.0−1.5 Hz for 2′-H, and as a doublet of doublets at δ = 5.76−6.14 with J = 18.5 and 4.4−7.0 Hz for 1′H. The large coupling constants of 18.0−18.5 Hz clearly indicate that the vinylsilane possesses the *E* configuration. The relative *trans*-configuration of the substituents at the two stereogenic centres of products **11a** and **11b** was confirmed by ^{1}H NMR NOESY experiments.

Conclusion

The directing ability of the TMS group is demonstrated by the intramolecular Heck reaction of the substrates **1a−c** and **2** containing an allylsilane moiety, resulting in the regioselective formation of the products **11a−c** with a trimethylsilylvinyl side chain. We assume that an intermediate Pd^+ species is formed, at least when using substrates **1**, which then undergoes a rapid PdL_nH^+ elimination of the more acidic hydrogen in the *α*-position to the trimethylsilyl group.

Experimental Section

General Remarks: Pd-catalysed transformations and reactions of air sensitive compounds were carried out in an inert atmosphere. − ^{1}H NMR and ^{13}C NMR spectra: Varian XL-200, VXR-200, Bruker AMX-300. − IR: Bruker IFS-25. − MS and HMRS: Varian MAT 311A and MAT 731. − UV/Vis: Perkin−Elmer Lambda 2. − Elemental analyses: Analytical laboratory of the University of Göttingen. − Column chromatography: Macherey, Nagel GmbH & Co. KG silica gel (0.063−0.200 mm). − Analytical TLC: Macherey, Nagel GmbH & Co. KG (SIL G/UV_{254}). − Gas chromatography: Varian 3400cx with FID, N_2 (3 mL/min), H_2 (200 kPa), Integrator Merck-Hitachi D-2000; columns: 1) SGE BPX-5% phenyl (equiv.) polysilphenylene-siloxane, 50 m; 2) octakis-(6-*O*-methyl-2,3-di-*O*-pentyl)-γ-cyclodextrin (50% in OV 1701, w/w), 25 m. − Solvents (distilled from): Et_2O (KOH or Na/benzophenone), pentane (KOH), EtOAc (CaH_2) THF ($LiAlH_4$).

General Procedure I: To a stirred solution of $KN(SiMe_3)_2$ (1.5 equivalents, 0.5 M in toluene) in dry THF (1 mL/mmol) was added

cyclohexanone (1.5 equivalents) at −78 °C, and stirring was continued at −78 °C for 2 h. Then the iodide (1.0 equivalents) in THF (1 mL/mmol) was added and the mixture was stirred for 2 h at room temperature, diluted with aqueous $NaHCO_3$ (20 mL/mmol) and extracted with pentane/Et_2O (9:1, 50 mL/mmol). The organic phase was washed with 1 N aqueous HCl (20 mL/mmol), aqueous $NaHCO_3$ (20 mL/mmol), and brine (50 mL/mmol). The aqueous phase was extracted with Et_2O (3 × 20 mL), the combined organic phases were dried over Na_2SO_4, and the solvent was removed in vacuo. The residue was purified by column chromatography.

General Procedure II: To a solution of diisopropylamine (1.2 equivalents) in THF (1 mmol/mL) was added *n*BuLi (1.2 equivalents, 1.6 M in hexane) at −78 °C. The solution was stirred for 1 h at −78 °C, 1 h at 0 °C and then cooled again to −78 °C. The ketone (1.0 equivalent) in THF (1 mmol/mL) was added, the mixture was stirred for 3 h at −78 °C, and then Tf_2NPh (1.1 equivalents) in THF (1 mmol/mL) was added. The reaction mixture was stirred for 15 h at 0 °C and then diluted with pentane (50 mL/mmol), and washed with water (20 mL/mmol) and brine (20 mL/mmol). The organic phase was dried over Na_2SO_4, concentrated in vacuo, and the residue purified by column chromatography.

(2*RS*)-(*Z*)-2-(3-Pentenyl-5-trimethylsilyl)cyclohexanone (5a): Reaction of cyclohexenone **3** (0.55 g, 5.60 mmol) with **4a** (1.00 g, 3.73 mmol) according to general procedure I gave 0.308 g (1.29 mmol, 35%) of the monoalkylated species **5a**. − R_f = 0.36 (pentane/EtOAc = 50:1). − IR (KBr): $\tilde{\nu}$ = 3005 cm^{-1} (C=CH), 2935, 2860 (CH), 1712 (C=O), 1645 (C=C), 1449 (CH), 857 ($SiMe_3$). − UV (CH_3CN): λ_{max} (lg ε) = 277.5 nm (1.670), 256.5 (2.651). − ^{1}H NMR (200 MHz, $CDCl_3$): δ = 0.00 (s, 9 H, $SiMe_3$), 1.25−1.28 (m, 2 H, 4-H), 1.46 (d, *J* = 8.3 Hz, 2 H, 5′-H), 1.58−2.08 (m, 8 H, 1′-H, 2′-H, 3-H, 5-H), 2.27−2.38 (m, 3 H, 6-H, 2-H), 5.14−5.50 (m, 2 H, 3′-H, 4′-H). − ^{13}C NMR (75.5 MHz, $CDCl_3$): δ = −1.8 ($SiMe_3$), 18.4 (C-5′), 24.5 (C-2′*), 24.9 (C-5*), 28.0 (C-1′), 29.4 (C-4), 34.0 (C-3), 42.0 (C-6), 50.1 (C-2), 126.0 (C-4′), 127.0 (C-3′), 213.4 (C-1). − MS (70 eV): *m/z* (%) = 238 (4) [M^+], 183 (46), 140 (28), 73 (100) [$SiMe_3^+$]. − $C_{14}H_{26}OSi$ (238.4): calcd. C 70.51, H 10.99; found C 70.72, H 11.11.

(6*RS*)-(*Z*)-Trifluoromethanesulfonic Acid 6-(3-Pentenyl-5-trimethylsilyl)-1-cyclohexenyl Ester (1a): Ketone **5a** (230 mg, 0.965 mmol) was deprotonated with LDA (1.16 mmol) in THF and reacted with Tf_2NPh (414 mg, 1.16 mmol) according to general procedure II. Chromatographic purification gave 283 mg (0.76 mmol, 79%) of **1a** as a colourless oil. − R_f = 0.67 (pentane/EtOAc = 50:1). − IR (KBr): $\tilde{\nu}$ = 3005 cm^{-1} (C=CH), 2936 (CH), 1681, 1645 (C=C), 1448 (CH, SO_2−O), 857 ($SiMe_3$). − UV (CH_3CN): no absorption. − ^{1}H NMR (200 MHz, $CDCl_3$): δ = 0.02 (s, 9 H, $SiMe_3$), 1.34−1.42 (m, 2 H, 5-H), 1.47 (d, *J* = 8.0 Hz, 2 H, 5′-H), 1.51−2.05 (m, 6 H, 2′-H, 1′-H, 4-H), 2.07−2.22 (m, 2 H, 3-H), 2.46 (m_C, 1 H, 6-H), 5.12−5.28 (m, 1 H, 3′-H), 5.35−5.51 (m, 1 H, 4′-H), 5.76 (dt, *J* = 4.0, 1.0 Hz, 1 H, 2-H). − ^{13}C NMR (50.3 MHz, $CDCl_3$): δ = −1.8 ($SiMe_3$), 18.5 (C-5′), 19.0 (C-1′), 24.1 (C-2′), 24.3 (C-3), 27.9 (C-4), 31.4 (C-5), 37.0 (C-6), 118.4 (q, *J* = 321 Hz, CF_3), 118.7 (C-2), 126.2 (C-4′), 126.4 (C-3′), 152.5 (C-1). − MS (DCI): *m/z* (%) = 405 (12) [M + NH_4^+ + NH_3], 388 (100) [M^+], 374 (0.1) [M − CH_3 + NH_4^+]. − $C_{15}H_{25}F_3O_3SSi$ (370.5).

(2*RS*)-(*Z*)-2-(4-Hexenyl-6-trimethylsilyl)-cyclohexanone (5b): Reaction of cyclohexenone **3** (0.130 g, 1.33 mmol) with **4b** (250 mg, 0.886 mmol) according to general procedure I gave 159 mg (0.630 mmol, 71%) of the monoalkylated species **5b**. − R_f = 0.34 (pentane/EtOAc = 70:1). − IR (KBr): $\tilde{\nu}$ = 3005 cm^{-1} (C=CH), 2935, 2860 (CH), 1712 (C=O), 1645 (C=C), 1449 (CH), 1247, 855 ($SiMe_3$). − ^{1}H NMR (200 MHz, $CDCl_3$): δ = 0.00 (s, 9 H, $SiMe_3$), 1.27−1.41 (m, 4 H, 2′-H, 4-H), 1.46 (d, *J* = 8 Hz, 2 H, 6′-H), 1.66−2.37 (m, 11 H, 2-H, 3-H, 5-H, 6-H, 1′-H, 3′-H), 5.16−5.50 (m, 2 H, 4′-H, 5′-H). − ^{13}C NMR (50.3 MHz, $CDCl_3$): δ = −1.8 ($SiMe_3$), 18.4 (C-6′), 24.8 (C-5), 27.2 (C-3′*), 27.3 (C-2′*), 28.0 (C-1′*), 29.2 (C-4), 33.8 (C-3), 41.9 (C-6), 50.7 (C-2), 125.5 (C-5′), 127.2 (C-4′), 213.4 (C-1). − MS (70 eV): *m/z* (%) = 252 (4) [M^+], 237 (6), [M^+ −CH_3], 209 (28) [M^+ − C_3H_7], 73 (100) [$SiMe_3^+$]. − $C_{15}H_{28}OSi$ (252.5): calcd. C 71.36, H 11.18; found C 71.36, H 11.14.

(6*RS*)-(*Z*)-Trifluoromethanesulfonic Acid 6-(4-Hexenyl-6-trimethylsilyl)-1-cyclohexenyl Ester (1b): Ketone **5b** (400 mg, 1.58 mmol) was deprotonated with LDA (1.90 mmol) in THF and reacted with Tf_2NPh (622 mg, 1.74 mmol) according to general procedure II. Chromatographic purification gave 501 mg (1.41 mmol, 89%) of **1b** as a colorless oil. − R_f = 0. 27 (pentane). − IR (KBr): $\tilde{\nu}$ = 3007 cm^{-1} (C=CH), 2949 (CH), 1680, 1646 (C=C), 1417 (CH), 1247, 1209 (SO_2−O), 858 ($SiMe_3$). − ^{1}H NMR (500 MHz, $CDCl_3$): δ = 0.00 (s, 9 H, $SiMe_3$), 1.30−1.44 (m, 3 H, 2′-H, 5-H_a), 1.45 (d, *J* = 8.5 Hz, 2 H, 6′-H), 1.51−1.73 (m, 4 H, 4-H_a, 5-H_b, 1′-H), 1.82−1.90 (m, 1 H, 4-H_b), 1.95−2.10 (m, 2 H, 3′-H), 2.12−2.16 (m, 2 H, 3-H), 2.42 (m_C, 1 H, 6-H), 5.20−5.26 (m, 1 H, 4′-H), 5.35−5.41 (m, 1 H, 5′-H), 5.72 (dt, *J* = 4, 1 Hz, 1 H, 2-H). − ^{13}C NMR (50.3 MHz, $CDCl_3$): δ = −1.8 ($SiMe_3$), 18.5 (C-6′), 19.1 (C-1′), 24.3 (C-3), 26.7 (C-2′), 27.0 (C-3′), 28.0 (C-4), 31.2 (C-5), 37.3 (C-6), 118.5 (q, *J* = 319 Hz, CF_3), 118.7 (C-2), 125.9 (C-5′), 126.8 (C-4′), 152.6 (C-1). − MS (DCI): *m/z* (%) = 786.4 (0.5) [2 M + NH_4^+], 419 (4) [M + NH_3 + NH_4^+], 402 (100) [M + NH_4^+]. − $C_{16}H_{27}F_3O_3SSi$ (384.5): calcd. C 49.98, H 7.08; found C 50.03, H 6.99.

(*Z*)-2-(5-Heptenyl-7-trimethylsilyl)-cyclohexanone (5c): Reaction of cyclohexanone **3** (0.50 g, 5.1 mmol) with the iodide **4c** (1.00 g, 3.38 mmol) according to the general procedure I gave 0.46 g (1.72 mmol, 51%) of **5c**. − R_f = 0.32 (pentane/EtOAc 50:1). − IR (KBr): $\tilde{\nu}$ = 3005 cm^{-1} (C=CH), 2933, 2858 (CH), 1713 (C=O), 1645 (C=C), 1449 (CH), 856 ($SiMe_3$) − ^{1}H NMR (200 MHz, $CDCl_3$): δ = 0.00 (s, 9 H, $SiMe_3$), 1.10−1.38 (m, 6 H, 2′-H, 3′-H, 4-H), 1.46 (d, *J* = 7.5 Hz, 2 H, 7′-H), 1.60−2.48 (m, 11 H, 3-H, 5-H, 1′-H, 4′-H, 6-H, 2-H), 5.17−5.48 (m, 2 H, 5′-H, 6′-H). − ^{13}C NMR (50.3 MHz, $CDCl_3$): δ = −1.8 ($SiMe_3$), 18.4 (C-7′), 24.8 (C-5), 27.0 (C-4′), 28.0 (C-2′), 29.3 (C-1′*), 29.3 (C-4*), 29.9 (C-3′*), 33.8 (C-3), 42.0 (C-6), 50.7 (C-2), 125.3 (C-6′), 127.5 (C-5′), 213.5 (C-1). − MS (70 eV): *m/z* (%) = 266 (18) [M^+], 251 (0.5) [M^+ − CH_3], 183 (100). − $C_{16}H_{30}OSi$ (266.5): calcd. C 72.11, H 11.35; found C 72.26, H 11.27.

(6*RS*)-(*Z*)-Trifluoromethanesulfonic Acid 6-(5-Heptenyl-7-trimethylsilyl)-1-cyclohexenyl Ester (1c): Reaction of **5c** (500 mg, 1.88 mmol) with LDA (2.26 mmol) and Tf_2NPh (806 mg, 2.26 mmol) according to general procedure II gave 0.60 g (1.51 mmol, 80%) of **1c** as a colourless oil. − R_f = 0.72 (pentane/EtOAc 50:1). − IR (film): $\tilde{\nu}$ = 3007 cm^{-1} (C=CH), 2939, 2862 (CH), 1680, 1645 (C=C), 1418, 1210 (SO−O), 855 ($SiMe_3$). − ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.01 (s, 9 H, $SiMe_3$), 1.27−1.40 (m, 5 H, 2′-H, 3′-H, 5-H_a), 1.47 (d, *J* = 9.0 Hz, 2 H, 7′-H), 1.53−1.72 (m, 4 H, 1′-H, 5-H_b, 4-H_a), 1.80−1.90 (m, 1 H, 4-H_b), 1.95− 2.05 (q, *J* = 7 Hz, 2 H, 4′-H), 2.10−2.19 (m, 2 H, 3-H), 2.42 (m_C, 1 H, 6-H), 5.23−5.28 (m, 1 H, 5′-H), 5.38−5.43 (m, 1 H, 6′-H), 5.75 (dt, *J* = 4.0, 1.0 Hz, 1 H, 2-H). − ^{13}C NMR (50.3 MHz, $CDCl_3$): δ = −1.8 ($SiMe_3$), 18.4 (C-7′), 19.1 (C-1′), 24.3 (C-3), 26.2 (C-2′*), 26.9 (C-3′*), 27.9 (C-4), 29.7 (C-4′), 31.3 (C-5), 37.3 (C-6), 118.5 (q, *J* = 321 Hz, CF_3), 118.6 (C-2), 125.6 (C-6′), 127.2 (C-5′), 152.7 (C-1). − MS

(DCI): *m/z* (%) = 814 (0.1) [2 × M + NH_4^+], 433 (2) [M + NH_3 + NH_4^+], 416 (100) [M + NH_4^+]. − $C_{17}H_{29}F_3O_3SSi$ (398.6).

(6*RS*)-(*Z*)-1-Iodo-6-(4-hexenyl-6-trimethylsilyl)-1-cyclohexene (2): A degassed solution of **1b** (358 mg, 1.00 mmol), hexamethyldistannane (362 mg, 1.10 mmol), LiCl (268 mg, 6.32 mmol) and $Pd(PPh_3)_4$ (23.2 mg, 0.020 mmol) in 5 mL of dry THF was stirred at 60 °C for 16 h. Then the mixture was cooled to room temperature and iodine (0.51 g, 2.00 mmol) in 2 mL of dry THF was added. After additional stirring for 20 h at room temperature, the mixture was diluted with saturated aqueous $Na_2S_2O_3$ (5 mL) and extracted with diethyl ether (10 mL). The combined organic phases were washed with brine (5 mL) and concentrated in vacuo. Chromatographic purification (pentane) gave 243 mg (0.67 mmol, 67%) of **2**. − R_f = 0.66 (pentane). − IR (film): $\tilde{\nu}$ = 3005 cm^{-1} (C=CH), 2934, 2858 (CH), 1645 (C=C), 1455 (CH), 1247, 857 ($SiMe_3$). − UV (CH_3CN): λ_{max} (lg ε) = 256.0 nm (2.978). − ^{1}H NMR (200 MHz, $CDCl_3$): δ = −0.01 (s, 9 H, $SiMe_3$), 1.12−1.44 (m, 3 H, 2′-H, 5-H_a), 1.47 (d, *J* = 8.0 Hz, 2 H, 6′-H), 1.50−1.87 (m, 5 H, 4-H, 5-H_b, 1-H), 1.87−2.12 (m, 4 H, 3-H, 3′-H), 2.18−2.37 (m, 1 H, 6-H), 5.20−5.50 (m, 2 H, 4′-H, 5′H), 6.36 (dt, *J* = 4.0, 1.5 Hz, 1 H, 2-H). − ^{13}C NMR (50.3 MHz, $CDCl_3$): δ = −1.7 ($SiMe_3$), 18.5 (C-6′), 27.0 (C-2′), 27.1 (C-3′, C-4), 28.1 (C-3), 29.6 (C-1′), 34.5 (C-5), 44.8 (C-6), 107.1 (C-1), 125.6 (C-5′), 127.2 (C-4′), 138.4 (C-2). − MS (70 eV): *m/z* (%) = 362 (1) [M^+], 235 (28) [M^+ − I], 161 (24) [M^+ − I − $SiMe_3$], 73 (100) [$SiMe_3^+$]. − $C_{15}H_{27}ISi$ (362.4): calcd. 362.0926, found 362.0926 (HRMS).

General Procedure III (Heck Reactions): A mixture of $Pd(OAc)_2$ (10 mol-%) and PPh_3 (20 mol-%) in dry THF or toluene was stirred at 45 °C for about 30 min to produce a homogeneous slurry. NEt_3 (2.0 equivalents) and the allylsilane were added and the mixture was heated at the indicated temperature until the reaction was completed (TLC). After cooling to room temperature and filtration through a short column of silica gel with Et_2O as eluent, the solution was concentrated in vacuo and the residue purified by chromatography on silica gel (pentane).

General Procedure IV (Heck Reactions): A mixture of $Pd_2(dba)_3{\cdot}CHCl_3$ (6−7 mol-%) and 1,4-bis(diphenylphosphano)butane (dppb) (12−14 mol-%) was stirred under Ar in DMF or dimethylacetamide (DMAA) at 45 °C for about 45 min to produce a homogeneous orange solution. Then KOAc (10 equivalents) and the allylsilane were added and the mixture was heated at the indicated temperature until completion (TLC). After cooling to room temperature, the mixture was diluted with Et_2O (20 mL/mmol) and washed with water and brine. The combined organic layers were dried over Na_2SO_4, concentrated in vacuo, and the residue was purified by column chromatography (pentane).

(1*RS*,3a*RS*)-(*E*)-1-(2-Trimethylsilylvinyl)-2,3,3a,4,5,6-hexahydro-1*H*-indene (11a) (Cyclisation of 1a): A: Reaction of **1a** (80 mg, 0.22 mmol) in 5 mL of toluene for 3 h at 80 °C according to general procedure III gave 45 mg (0.20 mmol, 93%) of the hexahydroindene **11a**. The diastereoselectivity was determined by GC as 90:10 (*trans*:*cis*).

B: Reaction of **1a** (70 mg, 0.19 mmol) in 3 mL of THF for 3 h at 65 °C according to general procedure III gave 37 mg (0.17 mmol, 89%) of the hexahydroindene **11a**. The diastereoselectivity was determined by GC as 80:20 (*trans*:*cis*). R_f = 0.88 (pentane). − GC (column 2, 50−150 °C, 3 °C/min): t_{R1} = 19.43 min (*trans*), t_{R2} = 20.07 min (*cis*), t_{R3} = 20.19 min (*cis*). − IR (film): $\tilde{\nu}$ = 2952 cm^{-1}, 2858 (C=CH, CH), 1674, 1615 (C=C), 1449 (CH), 1249, 841 ($SiMe_3$). − UV (CH_3CN): λ_{max} (lg ε) = 253.5 (4.476). − ^{1}H NMR (500 MHz, $CDCl_3$): *trans* diastereomer: δ = 0.00 (s, 9 H, $SiMe_3$), 0.94−1.06, 1.28−1.40, 1.40−1.50, 1.72−2.10 (m, 10 H, 2-H, 3-H, 4-H, 5-H, 6-H), 2.10−2.20 (m, 1 H, 3a-H), 3.00 (m_C, 1 H, 1-H), 5.35 (m_C, 1 H, 7-H), 5.54 (dd, *J* = 18.5, 1.5 Hz, 1 H, 2′-H), 5.90 (dd, *J* =18.5, 7.0 Hz, 1 H, 1′-H). − ^{13}C NMR (125.7 MHz, $CDCl_3$): *trans* diastereomer: δ = −1.1 ($SiMe_3$), 22.5 (C-6), 25.3 (C-5*), 29.1 (C-4*), 31.3 (C-2*), 33.0 (C-3*), 41.3 (C-3a), 50.3 (C-1), 119.1 (C-7), 127.3 (C-2′), 146.8 (C-7a), 150.4 (C-1′). − *cis* diastereomer: δ = −1.1 ($SiMe_3$), 22.5 (C-6), 25.1 (C-5*), 29.5 (C-4*), 30.5 (C-2*), 31.4 (C-3*), 40.5 (C-3a), 49.6 (C-1), 117.7 (C-7), 129.1 (C-2′), 147.4 (C-7a), 149.4 (C-1′). − MS (70 eV): *m/z* (%) = 220 (28) [M^+], 205 (12) [M^+ − CH_3], 146 (84) [M^+ − $HSiMe_3$], 73 (100) [$SiMe_3^+$]. − $C_{14}H_{24}Si$ (220.4): calcd. 220.1647, found 220.1647 (HRMS).

(1*RS*,4a*RS*)-(*E*)-1-(2-Trimethylsilylvinyl)-1,2,3,4,4a,5,6,7-octahydronaphthalene (11b): (Cyclisation of 1b). − A: Reaction of **1b** (95 mg, 0.25 mmol) in 5 mL of toluene at 75 °C for 2 h according to general procedure III gave 53 mg (0.23 mmol, 90%) of the octahydronaphthalene **11b.** The diastereoselectivity was determined by GC as 60:40 (*trans*:*cis*).

B: Reaction of **1b** (100 mg, 0.260 mmol) in 3 mL of THF for 3 h at 50 °C according to general procedure III gave 48 mg (0.21 mmol, 81%) of the octahydronaphthalene **11b**. The diastereoselectivity was determined by GC: 68:32 (*trans*:*cis*). R_f = 0. 81 (pentane). − GC (column 1, 130−230 °C, 5 °C/min): t_{R1} = 10.55 min (*trans*), t_{R2} = 12.07 min (*cis*). − IR (film): $\tilde{\nu}$ = 2931 cm^{-1}, 2860 (C=CH, CH), 1667 (C=C), 1447 (CH), 1248, 839 ($SiMe_3$). − ^{1}H NMR (500 MHz, $CDCl_3$): δ = 0.03 (s, 9 H, $SiMe_3$, *cis*), 0.05 (s, 9 H, $SiMe_3$, *trans*), 1.14−1.51, 1.54−1.81 (m, 21 H, 7-H_a, *cis*, 6-H, 5-H, 4-H, 3-H, 2-H, *cis* and *trans*), 1.95−1.98 (m, 3 H, 7-H, *trans*, 4a-H, *cis*), 2.03−2.10 (m, 2 H, 4a-H, *trans*, 7-H_b, *cis*), 2.48−2.55 (m, 1 H, 1-H, *cis*), 2.85−2.89 (m, 1 H, 1-H, *trans*), 5.28 (m_C, 1 H, 8-H, *cis*), 5.43 (m_C, 1 H, 8-H, *trans*), 5.62 (dd, *J* = 18.5, 2.0 Hz, 1 H, 2′-H, *trans*), 5.62 (dd, *J* = 18.5, 1.0 Hz, 1 H, 2′-H, *cis*), 6.03 (dd, *J* = 18.5, 7.6 Hz, 1 H, 1′-H, *cis*), 6.05 (dd, *J* = 18.5, 4.4 Hz, 1 H, 1′-H, *trans*). − ^{13}C NMR (50.3 MHz, $CDCl_3$): *trans* diastereomer: δ = −1.0 ($SiMe_3$), 21.7 (C-2*), 21.8 (C-3*), 25.8 (C-7*), 31.4 (C-4*), 32.4 (C-6*), 33.8 (C-4a), 35.4 (C-5), 48.9 (C-1), 122.0 (C-8), 128.7 (C-2′), 141.7 (C-8a), 150.4 (C-1′). − *cis* diastereomer: δ = −1.0 ($SiMe_3$), 21.3 (C-2*), 25.8 (C-7), 25.9 (C-3*), 31.3 (C-4*), 33.8 (C-6*), 35.3 (C-5), 37.8 (C-4a), 50.4 (C-1), 118.8 (C-8), 129.7 (C-2′), 143.2 (C-8a), 149.4 (C-1′). − MS (70 eV): *m/z* (%) = 234 (40) [M^+], 219 (8) [M^+ − CH_3], 160 (68) [M^+ − $HSiMe_3$], 73 (100) [$SiMe_3^+$]. − $C_{15}H_{26}Si$ (234.5): calcd. 234.1804, found 234.1803 (HRMS).

(2*RS*,7*RS*)-(*E*)-2-(2-Trimethylsilylvinyl)-bicyclo[5.4.0]undec-1(11)-ene (11c) (Cyclisation of 1c): Reaction of **1c** (63 mg, 0.16 mmol) in 3 mL of DMF for 16 h at 90 °C according to general procedure IV gave 24 mg (0.097 mmol, 61%) of bicycloundecene **11c**. The diastereoselectivity was determined by GC as 53:47. R_f = 0.78 (pentane). − GC (column 1, 100−250 °C, 5 °C/min): t_{R1} = 18.81 min, t_{R2} = 19.76 min. − IR (Film): $\tilde{\nu}$ = 2926 cm^{-1}, 2856 (C=CH), (CH), 1668 (C=C), 1453, 1378 (CH), 866 ($SiMe_3$). − ^{1}H NMR (500 MHz, $CDCl_3$): δ = 0.01 (s, 9 H, $SiMe_3$, isomer 1), 0.04 (s, 9 H, $SiMe_3$, isomer 2), 0.78−0.88, 1.25−1.80, 1.82−2.07 (m, 28 H, 3-H, 4-H, 5-H, 6-H, 8-H, 9-H, 10-H), 2.12 (m_C, 1 H, 7-H, isomer 1), 2.24 (m_C, 1 H, 7-H, isomer 2), 2.77 (m_C, 1 H, 2-H, isomer 1), 2.89 (m_C, 1 H, 2-H, isomer 2), 5.36 (m_C, 2 H, 11-H, both isomers), 5.52 (dd, *J* =18.0, 2.0 Hz, 1 H, 2′-H, isomer 1), 5.58 (dd, *J* = 18.0, 2.0 Hz, 1 H, 2′-H, isomer 2), 5.97 (dd, *J* = 18.0, 6.0 Hz, 1 H, 1′-H, isomer 1), 6.14 (dd, *J* = 18.0, 6.0 Hz, 1 H, 1′-H, isomer 2). − ^{13}C NMR (50.3 MHz, $CDCl_3$): δ = −0.99 ($SiMe_3$ isomer 1), −1.02 ($SiMe_3$, isomer 2), 18.8, 20.5, 25.4, 25.5, 25.8, 27.0, 27.9,

29.9, 31.2, 31.7, 32.9, 34.3, 34.8, 36.6 (C-3, C-4, C-5, C-6, C-8, C-9, C-10), 34.9, 38.6 (C-7), 49.1, 53.1 (C-2), 122.5, 123.8 (C-11), 126.3, 126.5 (C-2′), 143.6, 144.1 (C-1), 151.1, 151.4 (C-1′). – MS (70 eV): *m*/*z* (%) = 248 (60) [M^+], 233 (28) [$M^+ - CH_3$], 174 (100) [$M^+ - HSiMe_3$], 73 (100) [$SiMe_3^+$]. – $C_{16}H_{28}Si$ (248.5): calcd. 248.1960, found 248.1960 (HRMS).

Cyclisation of 2: Reaction of **2** (30 mg, 0.083 mmol) in 3 mL of DMF for 2 h at 80 °C according to general procedure IV gave 11 mg (0.047 mmol, 56%) of the octahydronaphthalene **11b**. The diastereoselectivity was determined by GC as 96:4 (*trans*:*cis*).

Cyclisation of Compound 7. – A: Reaction of **7** (100 mg, 0.320 mmol) in 5 mL of toluene for 4 h at 70 °C according to general procedure III gave 43 mg of a mixture of the compounds **12a**, (*E*)-**12b** and (*Z*)-**12b**. The yield of the compounds was determined by GC: (1*RS*,4a*RS*)-(*E*/*Z*)-1-vinyl-1,2,3,4,4a,5,6,7-octahydronaphthalene (**12a**): 33%, (4a*RS*)-(*E*/*Z*)-1-ethylidene-1,2,3,4,4a,5,6,7-octahydronaphthalene **12b**: 47%.

B: Reaction of **7** (100 mg, 0.320 mmol) in 5 mL of THF for 4 h at 65 °C according to general procedure III gave 42 mg of an inseparable mixture of the compounds **12a**, (*E*)-**12b** and (*Z*)-**12b**. The yield of the compounds was determined by GC: **12a**: 36%, **12b**: 45%.

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