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Controlling the Regiochemistry of Zirconocene-Catalyzed Hydrosilation of Styrenes. Selective Preparation of Markovnikov and Anti-Markovnikov Addition Products Using the Same Combination of Procatalysts

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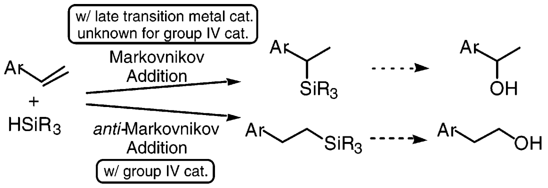
Summary: The catalytic system of Cp_2ZrCl_2 and n-BuLi (3 equiv with respect to Zr) promotes hydrosilation of styrene derivatives in the Markovnikov addition manner, which is the reverse regioselectivity compared to that for Zr-catalyzed olefin hydrosilation with the standard protocol ($Zr/n\text{-}BuLi = 1/2$).

Hydrosilation of olefins has been one of the most useful methods for functionalizing carbon−carbon double bonds.[1] Especially after discovery of the oxidation method of C−Si moieties into C−OH groups (Tamao oxidation),[2] the importance of olefin hydrosilation has been growing as the synthetic equivalent to olefin hydration giving the corresponding alcohols.

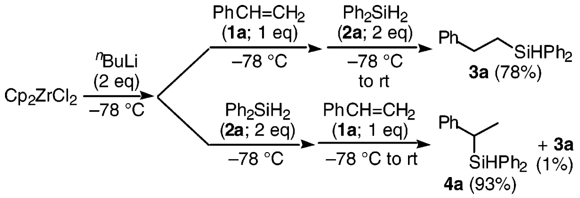
A major issue of the hydrosilation is regioselectivity of Si−H addition to a carbon−carbon double bond (Scheme 1). For example, anti-Markovnikov addition of a hydrosilane to a terminal olefin affords a primary alcohol after Tamao oxidation of the preformed alkylsilane. On the other hand, a secondary alcohol could be obtained from the same terminal olefin via Markovnikov addition of a hydrosilane. Generally, the two modes of Si−H addition may have be controlled by a proper choice of catalysts. Late-transition-metal catalysts with Ni, Pd, or Pt have the tendency to give Markovnikov addition products for hydrosilation of vinylarenes (styrenes),[1] while group IV metal catalysts give only anti-Markovnikov addition products for the same substrates, as our group and others reported.[3]

In this communication, we wish to report a unique method of controlling the two addition modes in the zirconocene-catalyzed hydrosilation of terminal styrene derivatives. Using the same combination of procatalyst species, namely Cp_2ZrCl_2 and alkyllithium, either of the two regioisomeric hydrosilation products could be *selectively* obtained by simply changing relative ratios of the two procatalysts.

Scheme 1



Scheme 2



A surprising reverse regioselectivity was observed in the hydrosilation of styrene using a stoichiometric zirconocene reagent. Treatment of Cp_2ZrCl_2 with *n*-BuLi (2 equiv) in THF at −78 °C for 1 h followed by successive addition of styrene (**1a**; 1 equiv with respect to Zr) and Ph_2SiH_2 (**2a**: 2 equiv with respect to Zr) in this order to the solution gave the anti-Markovnikov addition product **3a** exclusively in 78% yield, as we expected. On the other hand, the Markovnikov addition product **4a** was obtained unexpectedly in 93% yield together with a trace amount of **3a** (ca. 1%) when the addition order of **1a** and **2a** was changed: i.e., **2a** (2 equiv to Zr) was first added to the THF solution of Cp_2ZrCl_2/*n*-BuLi and then 1 equiv of **1a** was subsequently added to the solution (Scheme 2).

During further investigations on this unique regioselective addition of the hydrosilane to styrene, it was found that the regioselective hydrosilation could be realized even in the catalytic system. As reported previously,[3] when a mixture of **1a** (1.0 mmol) and **2a** (1.2 mmol) was treated with a zirconocene catalyst generated in situ from Cp_2ZrCl_2 (0.20 mmol) and *n*-BuLi

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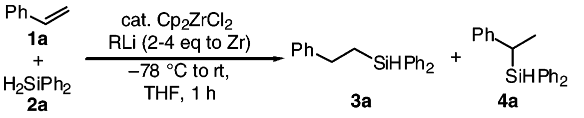
10.1021/om0493311 CCC: $27.50

Table 1. Zirconium-Catalyzed Regioselective Hydrosilation of Styrene[a]



entry	RLi (mol %)	[RLi]/[Zr]	**3a** (%)[b]	**4a** (%)[b]
1	*n*-BuLi (40)	2.0	92	0
2	*n*-BuLi (60)	3.0	0	98
3	*n*-BuLi (52)	2.6	11	81
4[c]	*n*-BuLi (52)	2.6	0	20
5	*s*-BuLi (40)	2.0	61	0
6	*s*-BuLi (64)	3.2	63	27
7	*s*-BuLi (80)	4.0	0	92
8	PhLi (40)	2.0	trace	0
9	PhLi (64)	3.2	0	98

[a] The reaction was carried out with **1a** (1.0 mmol) and **2a** (1.2 mmol) in THF at room temperature in the presence of zirconocene catalyst generated in situ from Cp_2ZrCl_2 (0.20 mmol) and RLi (2−4 equiv with respect to Cp_2ZrCl_2) at −78 °C. [b] Determined by GC analysis. [c] The reaction was performed at −78 to −20 °C.

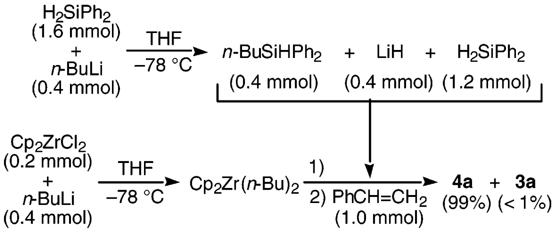
(0.40 mmol; 2 equiv with respect to Zr), hydrosilation proceeded smoothly at 20 °C, the anti-Markovnikov addition product **3a** was obtained exclusively in 92% yield, and no Markovnikov addition product was detected (GC and NMR analysis; Table 1, entry 1). When the reaction of **1a** (1.0 mmol) and **2a** (1.2 mmol) was performed in the presence of a zirconium catalyst generated in situ from Cp_2ZrCl_2 (0.20 mmol) and *n*-BuLi (0.60 mmol; 3 equiv to Zr), however, the reverse regioselectivity of hydrosilation was observed. The product from the latter reaction was found to be the Markovnikov addition product **4a**, which was obtained in 98% yield, and no **3a** was formed (entry 2).

Similar regioselectivity was seen for hydrosilation of **1a** catalyzed by Cp_2ZrCl_2 and *s*-BuLi, but the switching of the addition modes was not as clear as for the reactions using the Cp_2ZrCl_2/*n*-BuLi catalyst. With Cp_2ZrCl_2 (20 mol %) and *s*-BuLi (40 mol %), the anti-Markovnikov addition product **3a** was obtained in 61% yield exclusively (entry 5). As the amount of *s*-BuLi increased, formation of **4a** became dominant: with Cp_2ZrCl_2 (20 mol %)/*s*-BuLi (64 mol %) **3a** (63%) and **4a** (27%) were formed (entry 6), and with Cp_2ZrCl_2 (20 mol %)/*s*-BuLi (80 mol %) **4a** was obtained as the sole hydrosilation product in 92% yield (entry 7).

Reactions using a Cp_2ZrCl_2/PhLi system are more distinctive. With a mixture of Cp_2ZrCl_2 (0.20 mmol) and PhLi (0.40 mmol) at room temperature, virtually no hydrosilation proceeded and only a trace amount of **3a** was detected by GC (Table 1, entry 8). Cp_2ZrPh_2, produced from Cp_2ZrCl_2 and PhLi, is thermally stable under the reaction conditions, and thus the catalytically active species for the Zr-catalyzed anti-Markovnikov hydrosilation "Cp_2Zr^{II}" is not generated from Cp_2ZrCl_2 and PhLi at and below room temperature.[4] It was found, however, that a mixture of Cp_2ZrCl_2 and PhLi (3.2 equiv with respect to Zr) catalyzes the addition reaction of **2a** to **1a** in the Markovnikov addition manner and **4a** was obtained in 98% yield exclusively (entry 9).[5]

The catalytically active species for the anti-Markovnikov addition was proposed to be the transient divalent zirconocene Cp_2Zr^{II} (or $Cp_2Zr(\eta^2\text{-olefin})$),[3] which is generated in situ by thermal decomposition of Cp_2ZrR_2, where R is an alkyl group having β-hydrogen(s). $Cp_2Zr(n\text{-Bu})_2$, which is prepared from Cp_2ZrCl_2 and 2 equiv of *n*-BuLi at −78 °C, does not turn into the catalytically active species at and below −20 °C, because a higher temperature (ca. 20 °C or higher) is required for the thermal decomposition of zirconocene dibutyl.[6] On the other hand, Cp_2ZrCl_2 and *n*-BuLi (3 equiv) generate a catalytically active compound in the presence of hydrosilane (vide infra), even at −20 °C. The reaction of **1a** and **2a** at 20 °C with a mixture of Cp_2ZrCl_2 and *n*-BuLi in a 1:2.6 molar ratio afforded a mixture of **3a** and **4a** in 11% and 81% yields, respectively (Table 1, entry 3). The result could be explained as the existence of two catalytically active species in the reaction mixture. An analogous reaction with Cp_2ZrCl_2/*n*-BuLi (2.6 equiv with respect to Zr) at −20 °C gave **4a** in 20% yield exclusively, and no **3a** was produced (entry 4). At this temperature, formation of the active species for the anti-Markovnikov hydrosilation was effectively suppressed, and thus **4a** was selectively formed.

Scheme 3



Coexistence of hydrosilane and an extra amount of *n*-BuLi (or other organolithium reagents) is essential for the zirconocene-catalyzed Markovnikov hydrosilation. It was expected that the hydrosilane **2a** reacted with *n*-BuLi to form LiH and *n*-$BuSiHPh_2$.[7] Indeed, *n*-$BuSiHPh_2$ was isolated quantitatively when *n*-BuLi was treated with **2a** (excess) in THF at −78 °C for 1h, although confirmation of the LiH formation was difficult.[8] As shown in Scheme 3, addition of the independently prepared THF solution of *n*-$BuSiHPh_2$/LiH/SiH_2Ph_2 to a THF solution of $Cp_2Zr(n\text{-Bu})_2$ generated the Markovnikov hydrosilation catalyst and **4a** was formed in 99% yield together with a trace amount of **3a** (<1%).

The in situ generated LiH is probably solvated and soluble in THF. Thus, it reacts with Cp_2ZrR_2 to give the zirconate species $[Cp_2Zr(H)R_2]\cdot Li$ (**5**).[9] As a key inter-

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(5) In the reaction of **1a** and **2a** using EtMgBr as an activator of Cp_2ZrCl_2 in place of organolithium reagents, a large excess amount of the Grignard reagent is required to detect the Markovnikov addition product **3a** (with Zr/EtMgBr = 1/4, a mixture of **3a** (44%) and **4a** (38%) was obtained).

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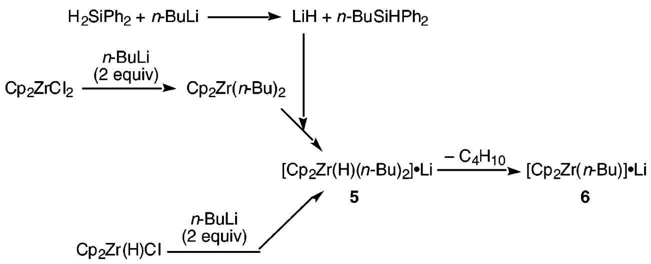
(8) Redistribution of substituents in di- and trihydrosilanes in the presence of inorganic hydrides has been reported, and this process may also be contributing to the present Zr-catalyzed hydrosilation. See: (a) Becker, B.; Corriu, R. J. P.; Guérin, C.; Henner, B. J. L. *J. Organomet. Chem.* **1989**, *369*, 147. (b) Woo, H.-G.; Kim, S.-Y.; Kim, W.-G.; Yeon, S. H.; Cho, E. J.; Jung, I. N. *Bull. Kor. Chem. Soc.* **1995**, *16*, 1109.

(9) (a) Fermin, M. C.; Stephan, D. W. *J. Am. Chem. Soc.* **1995**, *117*, 12645. (b) Etkin, N.; Hoskin, A. J.; Stephan, D. W. *J. Am. Chem. Soc.* **1997**, *119*, 11420.

Scheme 4

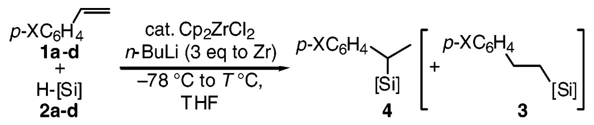


mediate for the Markovnikov hydrosilation, we propose the divalent zirconate species $[Cp_2Zr^{II}R]\cdot Li$ (**6**), which could be generated from $[Cp_2Zr^{IV}(H)R_2]\cdot Li$ by reductive elimination of RH (Scheme 4).[10] Commercially available LiH, which is insoluble in THF, has no effect on the regioselectivity of the Zr-catalyzed hydrosilation: the anti-Markovnikov product **3a** was formed from **1a** and **2a** using $Cp_2Zr(n\text{-}Bu)_2$ in the presence of solid LiH (excess).

As a THF-soluble hydride source, $LiBHEt_3$ was examined. A mixture of $Cp_2Zr(n\text{-}Bu)_2$ and $LiBHEt_3$ (1 equiv) catalyzed a reaction between **1a** and **2a**; however, the anti-Markovnikov addition product **3a** was obtained in >99% GC yield exclusively. Apparently, $LiBHEt_3$ was not functioning as a hydride source to the Zr center. It was found that BEt_3 prohibited the present Markovnikov hydrosilation and the addition mode was switched back to the usual anti-Markovnikov addition in the presence of BEt_3. The reaction of **1a** and **2a** with the zirconocene catalyst (20 mol %) generated from Cp_2ZrCl_2 and 3 equiv of *n*-BuLi in the presence of BEt_3 (1 equiv) afforded **3a** quantitatively, and no **4a** was detected. The Lewis acidic BEt_3 abstracted a butyl group from the zirconate **5** (or **6**) to generate the divalent neutral zirconocene species Cp_2Zr^{II}, which is the known catalyst for the anti-Markovnikov hydrosilation.[3]

The importance of a Zr−H species such as **5** in the current regioselective hydrosilation was also supported by reactions using Schwartz's reagent as a catalyst precursor. Treatment of a mixture of **1a** and **2a** with a Zr catalyst (20 mol %) generated from $Cp_2Zr(H)Cl$ and *n*-BuLi (2 equiv with respect to Zr) gave the Markovnikov addition product **4a** in 90% yield exclusively. The catalytically active species in this reaction is likely to be the zirconate **6**, the formation of which via the initially generated **5** can be explained as shown in Scheme 4. On the other hand, an equimolar mixture (20 mol %) of $Cp_2Zr(H)Cl$ and *n*-BuLi catalyzes the hydrosilation of **1a** with **2a** in an anti-Markovnikov fashion to give **3a** as the major product (81%) together with a small amount of **4a** (18%).

Table 2. Zirconium-Catalyzed Markovnikov Hydrosilation of Styrenes[a]



entry	X in **1**	[Si] in **2**	time (h)	T (°C)	**3** (%)[b]	**4** (%)[b]
1	F (**1b**)	$SiHPh_2$ (**2a**)	1	20	0	99 (**4b**)
2	Me (**1c**)	$SiHPh_2$ (**2a**)	1	20	0	>99 (76, **4c**)
3	MeO (**1d**)	$SiHPh_2$ (**2a**)	3	−20	0	85 (**4d**)
4	H (**1a**)	SiHPhMe (**2b**)	3	20	0	>99 (81, **4e**)
5	H (**1a**)	SiH_2Ph (**2c**)	3	20	0	70 (**4f**)
6	H (**1a**)	$SiHEt_2$ (**2d**)	1	20	0	27 (17, **4g**)

[a] The reaction was carried out with **1** (1.0 mmol) and **2** (1.2 mmol) in THF at the indicated temperature in the presence of zirconocene catalyst generated in situ from Cp_2ZrCl_2 (0.20 mmol) and *n*-BuLi (3 equiv with respect to Cp_2ZrCl_2) at −78 °C. [b] Determined by GC analysis. Isolated yields are given in parentheses.

The scope of the present Zr-catalyzed Markovnikov hydrosilation is broad (Table 2). Styrene derivatives having an electron-withdrawing group (entry 1) or an electron-donating group (entries 2 and 3) could be used as substrates. A wide range of mono- and disubstituted silanes **2b**−**d** (entries 4−6) are applicable to the reaction. In all cases, the internal silanes **4** were obtained exclusively when a mixture of Cp_2ZrCl_2 (20 mol %) and *n*-BuLi (3 equiv with respect to Zr) was employed as a catalyst, while the corresponding anti-Markovnikov products were formed under the reaction conditions described in our previous report (Cp_2ZrCl_2/*n*-BuLi = 1/2).[3a]

In summary, we have found that the catalytic system of Cp_2ZrCl_2 and *n*-BuLi (3 equiv with respect to Zr) promotes hydrosilation of styrene derivatives in the Markovnikov addition manner, which is the reverse regioselectivity compared to the Zr-catalyzed olefin hydrosilation with the standard protocol (Zr/*n*-BuLi = 1/2).

Supporting Information Available: Text giving detailed experimental procedures and compound characterization data. This material is available free of charge via the Internet at http://pubs.acs.org.

OM0493311

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