Cobalt-Catalyzed Hydrosilation/Hydrogen-Transfer Cascade Reaction: A New Route to Silyl Enol Ethers

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Silyl enol ethers are useful synthetic intermediates for a variety of C–C and C–X bond-forming processes.^[1] Traditional approaches to silyl enolate formation involve O-silylation of lithium enolates.^[2,3] These methods are incompatible with certain acidic functional groups and can require the use of protecting groups to prevent deleterious reactivity. Additionally, stoichiometric amounts of by-products and salts are formed as a result of these approaches. Recent transitionmetal-catalyzed methods to overcome the requirement for strong bases have included Ir-catalyzed carbonylative silylation,^[4] Rh-catalyzed aldehyde homologation,^[5] and Cu-catalyzed silyl migration.^[6] Dehydrogenative silylation of ketones has also been achieved by using Rh^[7] and Ru^[8] catalysts.

Recent work from our lab has shown that the [CoCp*- $(VTMS)_2$ complex 1 (VTMS = vinvltrimethylsilane) can be used in the activation of sp³ C-H bonds for the synthesis of enamines.^[9] Similar complexes have been used in hydrosilation^[10] and in hydrogen-transfer reactions.^[11] We postulated that with the appropriate silane reagent, 1 could catalyze a tandem hydrosilation/hydrogen-transfer cascade to produce silvl enol ethers [Eq. (1)]. This approach is appealing for two reasons. First, the reaction could be carried out under base-free conditions, opening the possibility of new substrate scopes. Second, the reaction would be atom economical, producing no stoichiometric salts or by-products. Herein, we report successful development of this methodology for the synthesis of silyl enol ethers. Additionally, we provide NMR evidence to support a unique η^2 -vinyl silane complex as the catalyst resting state during this transformation.

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Initial investigations into this approach focused on using acetophenone substrates with commercially available vinyl silanes. The vinyl silane serves three important roles. It acts

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as 1) the reducing agent for the ketone; 2) a directing group for the Co catalyst; 3) as the hydrogen acceptor for hydrogen transfer. In initial experiments, we were pleased to discover $[CoCp^*(VTMS)_2]$ catalyzed the desired reaction at room temperature overnight. By using one equivalent of silane, the reaction did not achieve completion after 8 h (Table 1, entry 1). Increased loading of silane (R=Me) resulted in full conversion (Table 1, entries 2 and 3). The reac-

Table 1. Optimization of silyl enol ether formation.^[a]

	O V	R∡ + Me ≁	Si ^H [Coo	Cp*(VTMS) ₂] solvent	\bigcirc	R₄Si,Me OSI
Entry	[mol %]	R	Silane	Solvent	t	Conversion ^[b]
			[equiv]		[h]	[%]
1	5	Me	1	toluene	8	71
2	5	Me	1.5	toluene	8	95
3	5	Me	2.0	toluene	8	100
4	5	Me	2.0	benzene	8	100
5	5	Me	2.0	CDCl ₃	15	decomp
6	5	Me	2.0	CD_2Cl_2	15	decomp
7	2.5	Me	2.0	toluene	9	99
8	1.0	Me	2.0	toluene	18	82
9	5	Ph	2.0	toluene	9	100
10	2.5	Ph	1.5	toluene	15	99
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[a] Reaction conditions: acetophenone (0.076 mmol) with $[CoCp^*(VTMS)_2]$ (0.76–3.8 µmol) and silane (0.076–0.15 mmol) in deuterated solvent (0.7 mL). [b] Monitored by ¹H NMR spectroscopy.

tion worked equally well in benzene and toluene (Table 1, entries 3 and 4). Halogenated solvents appeared to cause catalyst decomposition. In these reactions the solution turned green, and ¹H NMR analysis failed to show any recognizable resonances, suggesting a paramagnetic Co complex (Table 1, entries 5 and 6). The catalyst loading could be reduced to as low as 1 mol % while still obtaining acceptable conversions (Table 1, entries 7 and 8). Finally, the phenyl-substituted vinyl silane (R=Ph) worked equally well, albeit with a reduced rate (Table 1, entries 9 and 10).

With these results in hand, other substrates were explored for this Co-catalyzed hydrosilation/hydrogen-transfer reaction by using both $Me_2(vinyl)$ silane and MePh(vinyl)silane. A number of alkyl-substituted acetophenones were viable substrates including 2- and 4-methyl acetophenone, as well as the more sterically hindered 2',4',6'-trimethylacetopheTable 2. Optimization of silvl enol ether formation.^[a] R .Me Me 2.5 mol % 1 0 toluene, RT Arv R = Me. Ph Entry Product R Conversion [h] [%]^[b] R ŚSi 1 Me Me 9 >99 2 0 Ph 15 >99 R / Me 10 > 993 Me 4 0 15 >99 Ph .Me >99 5 11 Me ŚSi \cap Ph 15 >99 6 R .Me >99 7 Me 12 Si 8 0 Ph 14 >99 9 Me 9 R Me >99 S 9 10 0 Ph >99 CI Me 10 >99 11 Me S 12 0 Ph 12 >99 >99 R Me 5 13 Me 14 Ph 6 >99 15 Me Me 12 >99 S Ph 14 >99 16 0

[a] Reaction conditions: ketone (0.15 mmol) with [CoCp*(VTMS)₂] (3.8 µmol) and silane (0.3 mmol) in deuterated solvent (0.7 mL). [b] Monitored by ¹H NMR spectroscopy. [c] Yields of the isolated product.

none (Table 2, entries 3-8). Halide-substituted acetophenones worked equally as well in this reaction; aryl-Cl and aryl-Br bonds were unreactive under the reaction conditions (Table 2, entries 9–12).

Additionally, highly electron-deficient compounds (Table 2, entries 13 and 14) and polycyclic aryl ketones were efficient substrates for silvl enol ether formation (Table 2, entries 15 and 16).

One important advantage of this protocol is the ease and practicality of work-up and isolation. Upon completion of the reaction (>99% conversion), a small amount of CHCl₃ was added to the solution. Stirring for 5-10 min, followed by filtration over Celite and removal of volatiles (including excess silane), resulted in analytically pure silyl enol ethers. Importantly, the solvents used in the workup must be kept dry and acid free (CHCl₃ stored over sieves and CaCO₃) to prevent hydrolysis of the products.

Over the course of the catalytic reaction when using Me₂-(vinyl)SiH, a hydride signal (-21.2 ppm, broad) was observed, indicating a cobalt hydride complex as a likely resting state in the catalytic cycle. To gain some insight into the mechanism of this reaction and obtain additional information about the unique reactivity of cobalt in hydrogen-transfer reactions, stoichiometric studies were performed. The [CoCp*(VTMS)₂] complex **1** was combined with different amounts of silane, and the reactions were monitored by ¹H NMR spectroscopy. Addition of 1–5 equiv of RMe-(vinyl)SiH (R=Me, Ph) to 1 in C_6D_6 revealed that only one equivalent of silane was required to displace two equivalents of VTMS and generate a new cobalt hydride complex [Eq. (2)].



The resulting species contained a hydride resonance consistent with that observed during catalysis $(\delta =$ -21.2 ppm).^[12] This new complex also contained a pair of ¹H doublets at 1.58 and 1.59 ppm with coupling constants of 12.0 and 9.6 Hz, respectively, as well as a 1H ddd at 2.31 (J=12.0, 9.6, 3.6 Hz). These new signals and coupling constants are consistent with a Co-coordinated vinyl moiety. Two new diastereotopic methyl signals at $\delta = 0.62$ and -0.29 ppm (both doublets with J=1.8 Hz) implied the silane was coordinated to cobalt as shown in 2. Although the shifts were consistent with the complex proposed, the splitting of the multiplet at $\delta = 2.31$ ppm and two methyl doublets indicated another proton correlation. A two-dimensional ¹H COSY NMR experiment revealed a weak correlation between H⁴ and H¹. To confirm this correlation, a selective homonuclear decoupling experiment was performed. With H⁴ decoupled, the ddd at $\delta = 2.31$ ppm was reduced to a dd with J = 12.0 and 9.6 Hz (Figure S1 in the Supporting Information). Additionally, the two methyl signals at $\delta = 0.62$ and -0.29 ppm were reduced to singlets (Figure S2) and S3 in the Supporting Information). These correlations not only explain the observed multiplet at $\delta = 2.31$ ppm but the magnitude of the coupling is also suggestive of a retained Si-H bond, consistent with a η^2 -silane complex 3.

Distinguishing between the classical silvl hydride structure 2 and the η^2 -silane structure 3 can be accomplished by ex-

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amining the ²⁹Si–¹H coupling constants. The ¹H NMR spectrum of the Co–H singlet at $\delta = -21.3$ ppm of **2** in [D₈]toluene is severely broadened at 20 °C (18 Hz width at half-height) by the quadrupolar Co nucleus (I=7/2) and makes detection of an ²⁹Si–H coupling constant problematic (Figure 1 A). However, low-temperature NMR studies re-



Figure 1. ¹H NMR signals in the hydride region at A) 20 °C and B) -50 °C.

vealed narrowing of the signal to 10 Hz at -50 °C, at which temperature the ²⁹Si–H satellites are clearly visible and allow accurate determination of $J_{\text{Si-H}}$ as 65 Hz (Figure 1 B). The value of this coupling constant is within the range of related Co η^2 -silane complexes, which typically fall between 40–160 Hz, whereas $J_{\text{Si-H}}$ values between terminal hydride and terminal silyl substituents are much smaller.^[13] This suggests a three-centered, two-electron interaction shown in **3** is a more accurate representation of the complex.^[14]

A similar series of experiments revealed that the analogous complex was formed when **1** was combined with PhMe(vinyl)SiH in [D₆]benzene. Two diastereomers were observed with hydride signals at $\delta = -20.62$ and -20.69 ppm. Two new ddd at $\delta = 2.77$ and 2.45 ppm were also observed corresponding to H¹ in diastereomers **4a** and **4b** (Figure 2). Selective decoupling of the hydride signals (H⁴) reduced the ddd's to dd's at $\delta = 2.77$ and 2.45 ppm (Figure S4 in the Supporting Information) illustrating the coupling between H⁴ and H¹ in each complex. Additionally, the



Figure 2. Proposed cobalt-hydride structures.

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proton shifts of the methyl peaks in each diastereomer were reduced to singlets in the decoupling experiment (see Figure S5 in the Supporting Information). The observed J_{Si-H} coupling constants of 66 and 67 Hz confirm that with PhMe-VinylSiH η^2 -silane complexes are formed (**4a** and **b**).

With the structure of the Co–H resting state confirmed the following preliminary mechanism is proposed (Figure 3). Two equivalents of VTMS were displaced from $[CoCp^*-(VTMS)_2]$ upon addition of RMeVinylSiH to give 3 (or 4),



Figure 3. Proposed catalytic cycle for silyl enol ether formation.

which are the resting states of the catalyst. Coordination of the ketone followed by hydrosilation and O–Si bond formation gave the Co^I intermediate **6**. The subsequent hydrogen transfer steps most likely follow a mechanism analogous to those proposed for related transformations.^[11] C–H activation followed by olefin insertion gives the cobaltacycle **7**. β -Hydride elimination and C–H reductive elimination generates the silyl enol ether and regenerates the Co^I catalyst.

In summary, we have disclosed a new Co-catalyzed approach for preparing silyl enol ethers from ketones. This reaction provides a base-free and atom-economic method for access to an important and versatile series of intermediates. It features a new tandem hydrosilation/hydrogen-transfer cascade with a unique η^2 -silane complex, characterized in situ by NMR spectroscopy, as the catalyst resting state.

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