Mukaiyama Aldol Reactions Catalyzed by Zirconocene Bis(triflate) Complexes: Stereochemistry and Mechanisms for C−C Bond Formation

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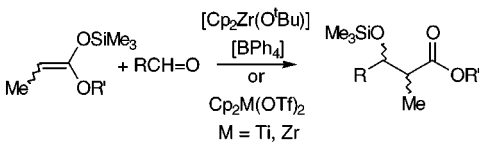
The aldol condensations of α- and *β*-(benzyloxy) aldehydes with enol silanes, catalyzed by $Cp_2Zr(OTf)_2$·THF or $Cp_2Zr(OTf)_2$, in a variety of solvents were studied. The simple diastereoselectivity of these reactions is modest and comparable to that observed using simple aldehydes of similar steric requirements. Studies have revealed that TMSOTf is directly produced on reaction with the zirconocene catalyst with the enol silane in nitroalkane solvent or is formed during catalysis in dichloromethane solution. Although TMSOTf is known to catalyze cross-aldol reactions under these conditions, the rate of this process is not always competitive with that observed using the zirconocene catalysts. In particular, sterically unhindered or aromatic aldehydes react via a mechanism that appears to be mainly Zr-catalyzed, based on both the difference in rate between Zr- and Si-mediated reactions as well as differences in enol silane/silyl triflate reactivity in crossover-type experiments. With sterically hindered aldehydes in dichloromethane or nitromethane, catalysis is mediated by Si. The Zr-catalyzed process occurs via formation of a Zr−aldolate complex from aldehyde and enol silane, with liberation of TMSOTf, followed by rate-limiting O-silylation of the metal aldolate by TMSOTf, as revealed by both model studies and in situ monitoring during catalysis.

Introduction

Several years ago, we described that the Mukaiyama cross-aldol condensation reaction could be catalyzed by cationic alkoxide complexes of Zr.[1] Somewhat earlier, Bosnich and co-workers reported that titanocene and zirconocene bis(triflate) complexes could also be employed as catalysts for this transformation (eq 1).[2] In the former

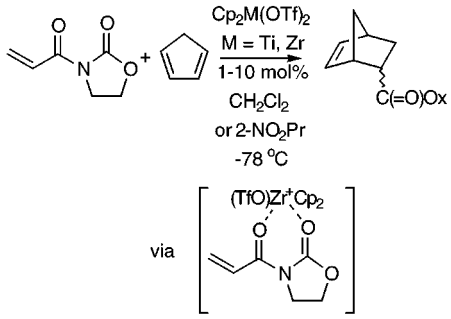


(1)

case, the simple diastereoselectivity of this reaction was modest but could be rationalized by acyclic transition states involving the enol silane and the aldehyde, activated by complexation to the metal center.

More recently, we have demonstrated that the Diels−Alder cycloaddition reaction between oxazolidinone-based dienophiles and cyclopentadiene can be efficiently catalyzed using metallocene bis(triflate)complexes (eq 2).[3] In the case of chiral catalysts, significant asymmetric induction was observed[3] and could be related to the formation of complexes in which the dienophile engages the metal center in a bidentate fashion under the reaction conditions.[4]

It had occurred to us that this latter feature might also be exploited in the Mukaiyama aldol reaction through



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the use of either α- or *β*-alkoxy aldehydes as substrates. High levels of chelation-controlled diastereoselectivity are frequently observed in reactions of enol silanes with such aldehydes (and related compounds) when the latter are activated by conventional Lewis acids.[5]

In this paper, we describe the aldol reactions of a number of aldehydes with enol silanes, mediated by zirconocene bis(triflate) complexes, and studies concerning the mechanism of this C−C bond forming reaction. This work complements that independently reported by Bosnich and co-workers using titanocene bis(triflate) complexes for simple aldehyde substrates[6] and indicates that the zirconocene analogues can behave quite differently in these reactions.

Results and Discussion

Aldol Reactions Employing α- and *β*-Alkoxy Aldehydes. The *β*- and α-(benzyloxy) aldehyde substrates

(1) Hong, Y.; Norris, D. J.; Collins, S. *J. Org. Chem.* **1993**, *58*, 3591.
(2) Hollis, T. K.; Robinson, N. P.; Bosnich, B. *Tetrahedron Lett.* **1992**, *33*, 6423.
(3) Jaquith, J. B.; Guan, J.; Wang, S.; Collins, S. *Organometallics* **1995**, *14*, 1079 and references therein.
(4) Jaquith, J. B.; Levy, C. J.; Bondar, G. V.; Collins, S. *Organometallics*, in press.
(5) For a review of synthetic applications see: Reetz, M. T. *Angew. Chem., Int. Ed. Engl.* **1984**, *23*, 556. For relevant mechanistic work see: (a) Reetz, M. T.; Raguse, B.; Seitz, T. *Tetrahedron* **1993**, *49*, 8561 and references therein. (b) Keck, G. E.; Castellino, S. J. *J. Am. Chem. Soc.* **1986**, *108*, 3847.
(6) Hollis, T. K.; Bosnich, B. *J. Am. Chem. Soc.* **1995**, *117*, 4570 and references therein.

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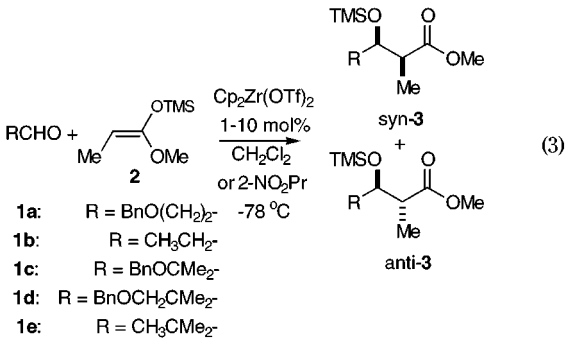
Table 1. Aldol Reactions Mediated by Zirconocene Bis(triflate) Complexes[a]

syn, anti - **3**

entry	triflate (mol %)	aldehyde (R)	solvent	syn:anti[b]	*T* (°C)	*t* (h)	*Y*[c] (%)
1	10	**1a** $BnO(CH_2)_2-$	2-NO_2Pr	1:1.48	−78	8	90
2	10[d]	**1a**	2-NO_2Pr	1:1.35	−78	5	90
3	10	**1b** CH_3CH_2-	2-NO_2Pr	1:1.05	−78	1.5	92
4	10	**1c** $BnOCMe_2-$	2-NO_2Pr	1.29:1	−78	10	85
5	10[d]	**1c**	2-NO_2Pr	1.57:1	−78	5	88
6	10	**1d** $BnOCH_2CMe_2-$	2-NO_2Pr	2.51:1	−78	5	89
7	1	**1d**	2-NO_2Pr	2.00:1	−78	10	92
8	10	**1d**	CH_2Cl_2	2.26:1	−78	5	85
9	1	**1d**	CH_2Cl_2	2.04:1	−78	10	90
10	10	**1e** Me_3C-	2-NO_2Pr	2.23:1	−78	1.5	97
11	1	**1e**	2-NO_2Pr	2.24:1	−78	8	94
12	10[d]	**1e**	2-NO_2Pr	2.07:1	−78	1.5	95

[a] Typical reaction scale: 0.5 mmol of aldehyde, 0.75 mmol of enolsilane, 2 mL of solvent. The aldehyde was added to the catalyst solution followed by the addition of enol silane, and they were both added in one portion. [b] Diastereoselectivity data is based on the analysis of ^1H and ^{13}C NMR spectra in conjunction with GC analyses (see Experimental Section). [c] Yields were determined by GC with reference to an *n*-decane as an internal standard. [d] $Cp_2Zr(OTf)_2$ was the catalyst.

1a, **1d**, and **1c**, shown in eq 3, were synthesized using either literature procedures or as described in the Experimental Section. They were selected as substrates



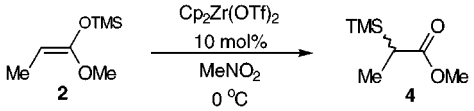
(3)

because the simple diastereoselectivity in their reactions with enol silanes could be directly compared to that of sterically similar, aldehydes **1b** and **1e**, respectively, under equivalent conditions. Chelation-controlled additions to the former substrates should result in enhanced 2,3-syn selectivity that should, in any event, differ significantly from that observed using simple aldehydes.

The results of a series of aldol reactions of aldehydes **1a**−**e** with enol silane **2**, conducted in $(CH_3)_2CHNO_2$ or CH_2Cl_2 solution at −78 °C in the presence of 1−10 mol % of either $Cp_2Zr(OTf)_2$·THF or $Cp_2Zr(OTf)_2$, are summarized in Table 1. The relative stereochemistry of the aldol products **5a**−**e** was established (after deprotection of the intermediate *β*-siloxy esters **3**) from the ^{13}C NMR chemical shifts of the C-2 methyl group as originally described by Heathcock and co-workers.[7] It should be pointed out that, in many cases, the intermediate *β*-siloxy esters **3** also exhibit the same NMR behavior as the aldol products themselves; the C-2 methyl group of the syn diastereomer resonates at higher field than in the corresponding anti isomer.

In all cases the simple diastereoselectivity of the reaction is modest. Sterically unhindered aldehydes **1a** and **1b** reacted to provide the 2,3-anti diastereomer "selectively", whereas with the more encumbered susbtrates **1c**−**e** the syn isomer predominated. There was a slight dependency of simple diastereoselectivity on catalyst loading; lower loadings tended to lead to lower selectivities. Thus, there appears to be very little difference in the level of diastereoselectivity using aldehydes capable of chelation to the metal center compared with their simpler counterparts. In fact, the stereochemical consequences of these reactions are qualitatively similar to those observed earlier using cationic alkoxide catalysts and simple aldehydes.[1]

The catalytic activity of the bis(triflate) complexes in reactions involving simple aldehyde substrates (i.e., **1b**,**e**) is similar to that of cationic alkoxide complexes in CH_2Cl_2 under equivalent conditions. However, in 2-nitropropane solution, these reactions are more rapid, although an excess of enol silane was required for complete consumption of the aldehyde substrates. We had earlier reported that cationic alkoxide complexes catalyze the isomerization of *O*-silylketene acetals to *C*-silyl esters (which do not participate in aldol reactions) in CH_2Cl_2 solution at higher temperatures.[1] Analogous experiments using $Cp_2Zr(OTf)_2$ and enol silane **2** revealed that this complex is also an effective catalyst for this process. Thus, the requirement for the use of an excess of enol silane in some of these reactions reflects competitive conversion of this material to the unreactive *C*-silyl isomer **4** (eq 4).



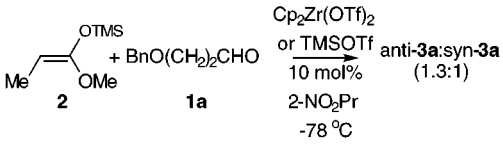
(4)

To demonstrate that these reactions were under kinetic control, a number of experiments were carried out using substrate **1e**. The syn/anti ratio of the product **3e** did not change with time during a typical reaction, as monitored by GC, and **3e**, depleted in the syn isomer (anti/syn ∼1:1.2), did not undergo equilibration under the conditions of the reaction, i.e., in the presence of enol silane **2** and $Cp_2Zr(OTf)_2$·THF. Some experiments were also performed to determine whether the stereoselectivity could be perturbed by the mode of addition of sub-

(7) Heathcock, C. H. In *Asymmetric Synthesis*; Morrison, J. D., Ed.; Academic Press: New York, 1984; Vol. 3, pp 115−118 and references therein.

strates: slow addition of **2** over 1 h to a mixture of **1d** and $Cp_2Zr(OTf)_2$·THF in 2-NO_2Pr failed to significantly affect the anti/syn ratio (1:1.85 vs 1:1.95), whereas inverse slow addition of **1d** did (anti/syn 1:1.35). Neither of these results is consistent with that expected for chelation-controlled additions to, e.g., aldehyde **1d**.

A more worrisome interpretation of the present results, especially in view of the results reported by Bosnich involving analogous reactions using $Cp_2Ti(OTf)_2$,[6] is that these reactions are not even mediated by the zirconocene catalyst, but by TMSOTf formed in situ. Indeed, a control experiment between aldehyde **1a** and **2** in the presence of TMSOTf (10 mol %) exhibited the same stereochemical outcome as observed in the presence of $Cp_2Zr(OTf)_2$·THF (eq 5). Having said that, under these conditions, the



(5)

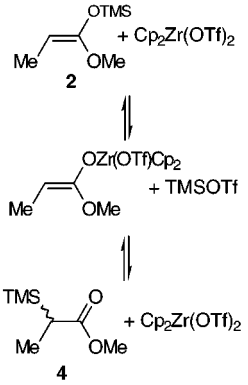
reaction of **2** with **1a** was complete after 1 h using the latter catalyst, whereas the conversion was only 40−50% after a similar period of time using TMSOTf at identical loadings.

In view of these uncertainties concerning the mechanism of this reaction, we elected to conduct a number of studies along these lines.

Mechanistic Studies

If TMSOTf is partially responsible for catalysis using $Cp_2Zr(OTf)_2$ and enol silane **2**, its in situ formation from these materials could be a necessary prerequisite. With this in mind, the reaction of these two compounds was studied in CD_2Cl_2 and CD_3NO_2 solution under stoichiometric conditions. In CD_2Cl_2 solvent, the isomerization reaction (eq 4) was not observed, and only trace quantities of trimethylsilyl triflate are present under these conditions. In CD_3NO_2 solution, enol silane **2**, in the presence of equimolar $Cp_2Zr(OTf)_2$, is converted to *C*-silyl ester **4**, a process that is complete after 2 h at −29 °C. Significant quantities (~10 mol % with respect to $Cp_2Zr(OTf)_2$ initially present) of TMSOTf (δ 0.52 ppm) are produced under these conditions, and unlike the situation reported by Bosnich[6] this material is *not* exclusively formed as a result of adventitious hydrolysis of the metal triflate complex. In particular, the expected hydrolysis coproducts, methyl propionate and hexamethyldisiloxane, were not formed in detectable quantities.

The results obtained in nitromethane solution suggest that there is an alternative mechanism for TMSOTf formation, possibly involving the (reversible) metathetical reaction shown in eq 6. A broadened singlet at δ 6.5 ppm was observed during these experiments and grew in intensity at the same rate as that of TMSOTf; this may correspond to the Zr(enolate) complex invoked below.[8] Consistent with this interpretation, the addition of excess TMSOTf resulted in the disappearance of this signal after the isomerization reaction was complete.[9]

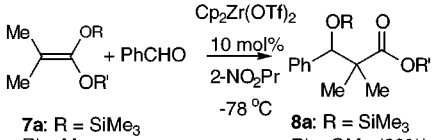


(6)

These experiments indicate that catalysis of the aldol reaction by TMSOTf is a possibility, particularly in nitroalkane solvents where significant amounts are present. Mechanisms that have been proposed for aldol condensations mediated by metal triflate catalysts are shown in Scheme 1.[6,10]

In the first of these, the metal activates the aldehyde to nucleophilic attack from enol silane and intramolecular transfer of the silyl group to the β-oxygen of the aldolate complex is rapid (path A). In a variation of this mechanism, the silyl group is rapidly transferred to another substrate (e.g., TfO^- ion) and it is reaction of the latter compound with the aldolate that gives rise to product formation (path B). Finally, TMSOTf, formed in situ by path B, may activate the aldehyde via silylation in what is basically a metal-initiated but Si-catalyzed pathway (path C), particularly when reaction of the metal aldolate with TMSOTf, via path B, is slow. Perversely, even the aldolate complex **6** may serve as source of electrophilic Si and could serve to activate aldehyde to nucleophilic attack via silyl transfer.

Path A can be distinguished from either B or C through an appropriate crossover experiment. In the present case, the reaction of benzaldehyde with enol silanes **7a** and **7b** was investigated.[11] The product mixture was analyzed by GC/MS, and the aldol products shown in eq 7 were formed in the amounts indicated after 1 h at −78 °C in 2-nitropropane. Thus, crossover is clearly extensive, and this is consistent with reaction occurring via either path B or C.



7a: R = $SiMe_3$, R' = Me
7b: R = $SiMe_2Bu$, R' = Et

8a: R = $SiMe_3$, R' = OMe (28%)
8b: R = $SiMe_3$, R' = OEt (22%)
8c: R = $SiMe_2Bu$, R' = OEt (21%)
8d: R = $SiMe_2Bu$, R' = OMe (29%)

(7)

Analogous experiments in CH_2Cl_2 at −78 °C using either 10 mol % $Cp_2Zr(OTf)_2$ or TMSOTf were quenched after 4 h at −78 °C. There were dramatic differences in

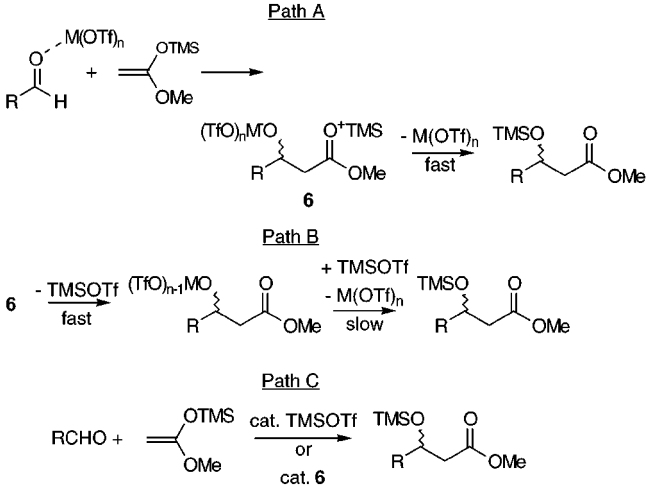
(8) A number of other signals were present that might be assigned to this intermediate, but their low intensity precluded unambiguous identification.

(9) It is quite possible that TMSOTf is also a catalyst for this isomerization process in nitroalkane solvents as the rate of isomerization qualitatively increased as the amount of TMSOTf increased.

(10) (a) Kobayashi, S.; Uchiro, H.; Shiina, I.; Mukaiyama, T. *Tetrahedron* **1993**, *49*, 1761. (b) Carreira, E. M.; Singer, R. A. *Tetrahedron Lett.* **1994**, *35*, 4323. (c) Denmark, S. E.; Chen, C. T. *Ibid.* **1994**, *35*, 4327.

(11) Qualitatively similar results were observed using **2** and PhCHO. However, quantitation was not possible due to the formation of syn and anti diastereomers, which were not adequately separated by GC.

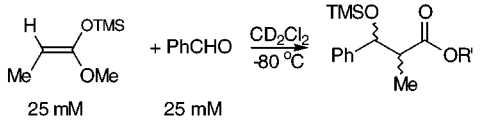
Scheme 1



product distribution. In particular, in the case of TMSOTf, although both products **8a** and **8b** were present (and in approximately the same amount), very little **8c** and **8d** were present, indicating the ^{n}BuMe$_2$SiOTf is a less effective catalyst under these conditions. The observation of all four products being (more rapidly) formed in the Zr reaction under the same conditions implies that there is a pathway for catalysis involving Zr and that it proceeds via path B. However, this experiment simply demonstrates that a Zr-catalyzed pathway is more rapid than an analogous process mediated by ^{n}BuMe$_2$SiOTf; it provides no insight into the importance of Zr-mediated processes compared with those catalyzed by TMSOTf.

To gauge the relative importance of the TMSOTf vs Zr-mediated pathways, it is necessary to quantitatively determine the rates of reaction. Although this was qualitatively alluded to earlier (eq 5), we felt it important to study this more carefully by ^{1}H NMR spectroscopy. It was not possible to study the Zr-mediated reaction in CD_3NO_2 solvent as the rates of reaction of PhCHO with enol silane **2**, even in dilute solution, were too fast for quantitative work (i.e., complete on mixing at −29 °C). We thus elected to look at reactions in CD_2Cl_2 solution at lower temperatures, although admittedly, formation of TMSOTf is less problematic in this solvent.

As shown in eq 8, the aldol reaction between PhCHO and enol silane **2**, catalyzed by $Cp_2Zr(OTf)_2$ (1 mol %), was extremely rapid even at −80 °C in CD_2Cl_2; the reaction was complete in the time required for the first acquisition following mixing (<5 min). In contrast, the



(8)

[Cat] = 0.25 mM	t_{95} (min)[a]	k_{obs} (M^{-1} s^{-1})
$Cp_2Zr(OTf)_2$	< 5	> 2.5
TMSOTf	20[b]	~ 0.6[b]

a. Time for > 95 % conversion of PhCHO.
b. The 1st spectrum showed ca. 50% conversion.
t_{95} is for 95% conversion.

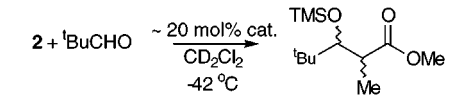
TMSOTf-mediated process is at least four times slower, reaching 95% conversion after ~20 min under the same conditions. Thus, in dry dichloromethane solution, where only trace quantities of TMSOTf are initially present, it is unlikely that path C is kinetically important. Given the crossover observed, the present results suggest that the aldol reaction involving PhCH=O and enol silanes is Zr-catalyzed and proceeds via path B.

This result, although reasonably compelling, was less satisfying since it was not possible to accurately measure rates of the Zr-mediated reaction in this case. To that end, we elected to study reactions involving ^{t}BuCH=O and enol silane **2** in the hope that these would prove sufficiently slow for more quantitative work by ^{1}H NMR spectroscopy.

This was indeed the case; reaction of enol silane **2** with ^{t}BuCH=O could be conveniently monitored by ^{1}H NMR in CD_2Cl_2 solution at −42 °C. As shown in Figure 1, clean second-order kinetics (first order in both aldehyde and enol silane) were observed in CD_2Cl_2 solution for either the TMSOTf-catalyzed reaction or the "Zr-catalyzed" process.

In the latter case, significant quantities of TMSOTf were formed during reaction, the amounts of which were effectively constant during the time period the reaction was monitored (ca. 2−3 half-lives) and were essentially equal to the amount of Zr catalyst initially present (i.e., ca. 10 mol % with respect to RCH=O). In addition, two line-broadened peaks were observed for the Cp protons during reaction, the appearance of which was dependent on temperature but independent of conversion. This behavior can be ascribed to formation of a Zr-based intermediate, the most likely candidate being a Zr-aldolate (Scheme 1, path B, vide infra). This species is either formed in situ from substrates and catalyst, and then no longer participates in the reaction (as in Bosnich's studies involving Ti "catalysts"[6]), or is capable of turnover by the mechanism outlined in path B (i.e., by reaction with TMSOTf) in analogy to results obtained using PhCH=O.

As shown in eq 9, the calculated values of the rate constant for catalysis in CD_2Cl_2 are essentially identical for the Zr- and Si-mediated reactions; it seems clear, in this case, that path C dominates. In CD_3NO_2 solvent at



(9)

Catalyst	[Cat] (M)	k_{obs} (10^{-3} M^{-1} s^{-1})	k (10^{-1} M^{-2} s^{-1})
$Cp_2Zr(OTf)_2$	0.026*	4.82 ± 0.25	1.85 ± 0.10
TMSOTf	0.040	8.06 ± 0.40	2.02 ± 0.10

* this is the concentration of TMSOTf formed in situ ~ [$Cp_2Zr(OTf)_2$].

− 30 °C, reaction was much more rapid (at identical loadings) and it was not possible to distinguish between the Si- and Zr-mediated reactions as they were essentially complete on mixing at this temperature. A lower estimate for the rate constant for both processes in CD_3NO_2 at −30 °C is ca. 0.6 M^{-1} s^{-1} based on >95% conversion within 5 min at $[RCH=O]_o = [\mathbf{2}]_o = 0.11$ M.

The viability of path B (vs path C) as a mechanism for catalysis can, in part, be gauged by examining the reaction of putative, metal aldolate product with TMSOTf. If the former compound does not react with TMSOTf to provide aldol products, it can be concluded that path B is not important and that the aldol reaction is Si-catalyzed (path C). In the present case, the likely intermediate involved is the metal aldolate **10** shown in eq 10b.

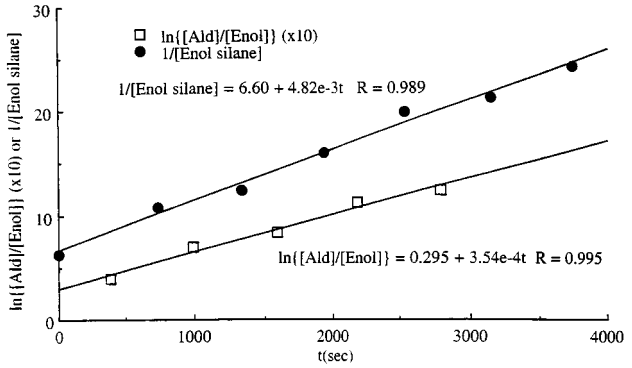
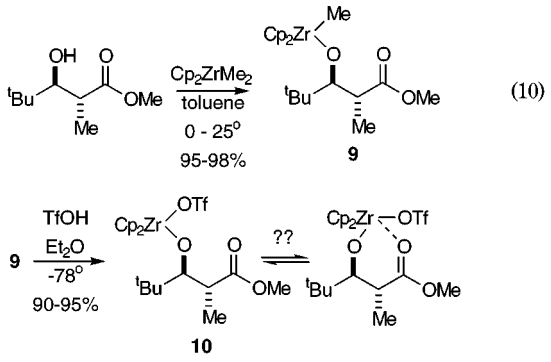


Figure 1. Aldol reactions between ^{t}BuCHO ([^{t}BuCHO]$_o$ = 0.161 and 0.170 M) and enol silane **2** ([**2**]$_o$ = 0.158 and 0.126 M) catalyzed by $Cp_2Zr(OTf)_2$ (0.026 M, circles) or TMSOTf (0.040 M, squares), respectively. The slopes are equal to k_{obs} = k[$Cp_2Zr(OTf)_2$] and k_{obs}([^{t}BuCHO]$_o$ − [**2**]$_o$) with k_{obs} = k[TMSOTf], respectively.

Preparation of the metal aldolate **10** was achieved through reaction of Cp_2ZrMe_2 with 1 equiv of the anti aldol derived from pivaldehyde (prepared via the lithium enolate followed by chromatographic separation of the anti isomer) in toluene (eq 10a), followed by reaction of aldolate **9** with 1 equiv of TfOH in diethyl ether at −78 °C (eq 10b). Complexes **9** and **10** were characterized by ^{1}H NMR spectroscopy but were not obtained as analytically pure compounds.



(10)

Interestingly, complex **10** is fluxional in solution on the NMR time scale. At room temperature, two line-broadened signals, due to the diastereotopic Cp protons, are present in toluene-d_8 while only a single, line-broadened peak is seen in CD_2Cl_2 solution. We tentatively attribute this behavior to reversible coordination of the C=O group to the metal center in this complex (eq 10b). At lower temperatures (in toluene-d_8 or CD_2Cl_2), only two sharp signals for the Cp protons were observed, which suggests that one of these isomers is highly favored at equilibrium (see Figure 2). The appearance of this spectrum in CD_2Cl_2 is very similar to that observed during catalysis and provides evidence for the intermediate formed during catalysis as being complex **10**.

When complex **10** (~0.05 M in CD_3NO_2 solution) was treated with a stoichiometric amount of TMSOTf at −30 °C, it was slowly transformed to *anti*-**3e** and $Cp_2Zr(OTf)_2$. An estimate of the second-order rate constant for this process was obtained and is 7.5 ± 1.5 × 10^{-3} M^{-1} s^{-1}. This is roughly 2 orders of magnitude slower than the *lower* limit estimated for the effective, second-order rate constant for reaction of ^{t}BuCH=O with [**2**] in CD_3NO_2 at the same temperature (vide supra). Thus, although turnover of **10** by reaction with TMSOTf is feasible, catalysis by TMSOTf (path C) dominates under these conditions.

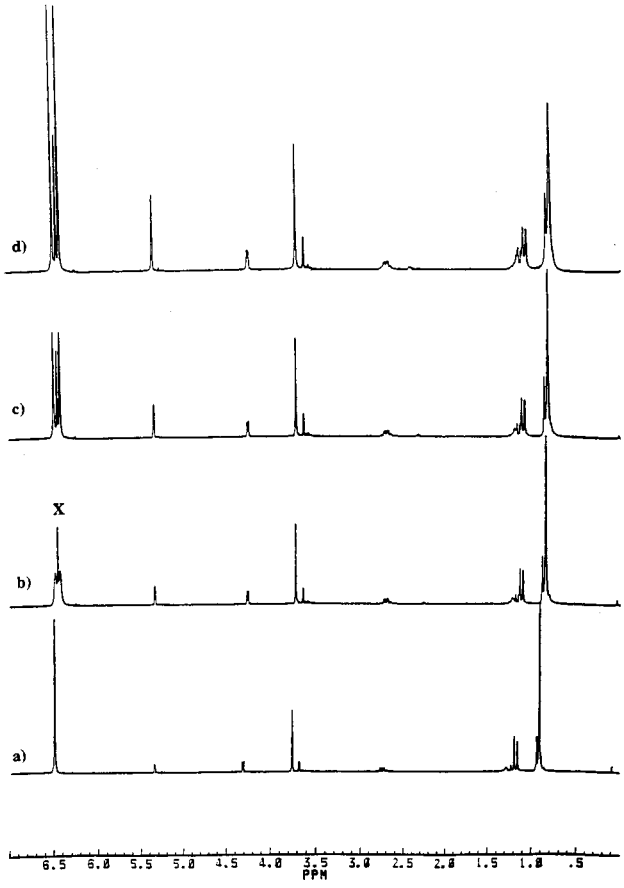


Figure 2. ^{1}H NMR spectra of zirconium aldolate **10** (300 MHz, CD_2Cl_2) at (a) 298, (b) 243, (c) 223, and (d) 203 K. The signal marked with an X is an unknown zirconocene impurity.

In CD_2Cl_2 solution at −40 °C, aldolate **10** did react with TMSOTf, but at a much slower rate than in CD_3NO_2. This again, in conjunction with the kinetic results reported earlier, strongly implicates that the reaction of ^{t}BuCH=O with enol silane **2** is Si-catalyzed. This may be a reflection that the turnover limiting step in the Zr-catalyzed process involves silylation of a quite sterically hindered, Zr-aldolate species and that this process is simply not competitive with the analogous silyl-transfer process. With sterically less hindered aldehydes (e.g., PhCH=O or **1a**), this does not appear to be the case.

Conclusions

The Mukaiyama aldol condensation between enol silanes and aldehydes, mediated by zirconocene bis(triflate) complexes, can proceed by both Zr- and Si-catalyzed pathways, in contrast to similar reactions involving analogous titanocene complexes, which are predominantly, if not exclusively, Si-catalyzed.[6] With aromatic aldehydes (and possibly, unhindered, aliphatic aldehydes, eq 5), the Zr-mediated process appears to dominate, whereas with sterically hindered, aliphatic aldehydes, both processes are competitive, but their relative importance is dependent on solvent polarity. In our opinion, the Zr-mediated reactions are favored, compared to Ti-catalyzed pathways, by the more open coordination

environment provided by the larger Zr atom in the aldolate intermediate. The rate of reaction involving a Zr−aldolate intermediate with TMSOTf should be sensitive to steric effects of the aldehyde substituent, and this is qualitatively supported by the relative importance of the two different pathways (i.e., Si- vs Zr-catalyzed) as a function of substrate structure.

It is clear that the sensitivity of the mechanism of this reaction to changes in aldehyde structure (i.e., path B or paths B and C, with either being dominant under appropriate conditions) as well as experimental conditions such as solvent polarity does not bode well for significant asymmetric induction using chiral zirconocene catalysts of this type.[12] Also, the level of simple diastereoselectivity in these reactions is disappointingly low, even for substrates capable of chelation to the metal center. It is possible that the aldehyde substrates examined do not readily form chelates with these catalysts under these conditions[13] and/or the rate of reaction of the unchelated form of the aldehyde complex with enol silane is competitive and/or faster. Future work, involving triflate-free catalyst systems, will be directed toward these problems.[14]

Experimental Section

All solvents and chemicals were reagent grade and purified as required. Tetrahydrofuran, diethyl ether, hexanes, and toluene were dried by distillation from sodium−benzophenone ketyl. Methylene chloride was dried by distillation from CaH_2. Nitromethane and 2-nitropropane were dried by distillation from $CaCl_2$ and were stored over activated MS 4 Å prior to use. All synthetic reactions were conducted under an atmosphere of dry nitrogen in dry glassware unless otherwise noted. $Cp_2Zr(OTf)_2$·THF and $Cp_2Zr(OTf)_2$ were prepared via literature procedures.[15] Enol silanes **2**, **7a**, and **7b** were prepared by silylation (R_3SiCl, THF, −78 to 0 °C) of the lithium enolates derived from the corresponding esters (LDA, THF, −78 °C).[16]

Routine ^1H and ^{13}C NMR spectra were recorded in $CDCl_3$ or C_6D_6 solution at 200 and 50 MHz or 250 and 62.5 MHz, respectively. Low-temperature ^1H NMR spectra were recorded in CD_2Cl_2 or CD_3NO_2 solution at 200 MHz using a properly calibrated thermocouple. IR spectra were recorded on an FTIR spectrometer. Mass spectra were obtained using an instrument at the University of Guelph. Gas chromatography was performed on a 0.25 mm × 50 m, SE-30 capillary column. GC−MS analyses were obtained on a 0.32 mm × 25 m HP-5 column. Elemental analyses were determined by M.H.W. Laboratories of Phoenix, AZ.

3-(Benzyloxy)propanal (1a). This compound was prepared from 1,3-propanediol as described in the literature.[17] The product was obtained a clear oil on Kugelrohr distillation (100 °C, 1 mmHg): ^1H NMR (250 MHz, $CDCl_3$) δ 9.78 (t, J = 2.0 Hz, 1H), 7.30 (m, 5 H), 4.53 (s, 2H), 3.82 (t, J = 6.8 Hz, 2H), 2.70 (dt, J = 6.8, 2.0 Hz, 2H).

2-(Benzyloxy)-2-methylpropanal (1c). This compound was prepared from 2-hydroxy-2-methylpropanoic acid by the following sequence: benzylation (2 equiv of NaH, excess BnBr, DMF, 25 °C) to provide a mixture of the benzyl ether and dibenzyl ether/ester, reduction (LAH, THF, reflux) and oxidation (PCC, CH_2Cl_2). The product was obtained as a colorless oil on distillation (90 °C, 1 mmHg): IR (thin film) 3064, 3031, 2980, 2933, 2869, 2804, 1735, 1456, 1386, 1170, 1058, 740, 697 cm^{-1}; ^1H NMR (250 MHz, $CDCl_3$) δ 9.64 (s, 1H), 7.35 (m, 5H), 4.46 (s, 2H), 1.35 (s, 6H); ^{13}C NMR (62.5 MHz, $CDCl_3$) δ 204.6, 138.7, 128.9, 128.2, 128.0, 80.9, 67.0, 21.4. Anal. Calcd for $C_{11}H_{14}O_2$: C, 74.13; H, 7.92. Found: C, 73.96; H, 8.11.

3-(Benzyloxy)-2,2-dimethylpropanal (1e). This compound was prepared from 2,2-dimethyl-1,3-propanediol as described in the literature:[18] ^1H NMR (250 MHz, $CDCl_3$) δ 9.55 (s, 1H), 7.30 (m, 5H), 4.49 (s, 2H), 3.44 (s, 2H), 1.08 (s, 6H).

Mukaiyama Aldol Reactions. Typical Procedure. A solution of $Cp_2Zr(OTf)_2$·THF (0.1 mmol) in 2.0 mL of dry solvent was cooled to −78 °C under nitrogen. The aldehyde (1.0 mmol) and enol silane (1.5 mmol) were then added via syringe. The reaction was monitored by either TLC or GC for consumption of the aldehyde. After the reaction was complete, the solution was diluted with hexane:ether 9:1 and filtered through a short pad of silica gel to remove catalyst, washing with additional hexane:ether 9:1. The filtrate was concentrated in vacuo to dryness to provide the crude aldol products (as the TMS ethers), which could be further purified by flash chromatrography on silica eluting with hexane:ether 9:1. The simple diastereoselectivity was determined either by ^1H NMR spectroscopy or GC prior to purification.

To determine stereochemistry, the crude mixture was directly converted to the free aldols (THF/AcOH/H_2O 8:1:1, 25 °C for **3a**,**b**; TBAF, THF/H_2O 9:1 for **3c**−**e** 25 °C), which could be purified by flash chromatrography on wet silica gel eluting with hexane/ethyl acetate 8:1 and whose spectroscopic and analytical data are summarized below:

Methyl 5-(benzyloxy)-3-hydroxy-2-methylpentanoate (2,3-*syn*- and -*anti*-5a): IR (thin film) 3464, 2948, 2867, 1728, 1455, 1363, 1201, 1097, 741, 699 cm^{-1}. Anal. Calcd for $C_{14}H_{20}O_4$: C, 66.65; H, 7.99. Found: C, 66.62; H, 7.85.

2,3-*syn*-5a: ^1H NMR (250 MHz, $CDCl_3$) δ 7.32 (m, 5H), 4.52 (s, 2H), 4.07 (m, 1H), 3.69 (s, 3H), 3.67 (m, overlapping, 2H), 3.19 (s, 1H, *syn*-OH), 2.57 (pseudo quint, superimposed, $J \approx$ 7.0 Hz, 1H), 1.83 (m, 2H), 1.19 (d, J = 7.0 Hz, 3H); ^{13}C NMR (62.5 MHz, $CDCl_3$) δ 175.7, 137.9, 128.3, 127.5, 127.4, 72.8, 72.0, 68.4, 51.5, 44.8, 33.7, 11.4 (*syn*-2-CH_3). **2,3-*anti*-5a**: ^1H NMR (250 MHz, $CDCl_3$) δ 7.32 (m, 5H), 4.52 (s, 2H), 3.94 (m, 1H), 3.72 (m, overlapping, 2H), 3.70 (s, 3H), 3.28 (s, 1H, *anti*-OH), 2.57 (pseudo quint, overlapping, $J \approx$ 7.1 Hz, 1H), 1.83 (m, 2H), 1.21 (d, J = 6.6 Hz, 3H); ^{13}C NMR (62.5 MHz, $CDCl_3$) δ 175.7, 137.9, 128.3, 127.5, 127.4, 73.1, 70.8, 68.2, 51.5, 45.4, 33.7, 13.5 (*anti*-2-CH_3).

Methyl 3-Hydroxy-2-methylpentanoate (2,3-*syn*- and -*anti*-5b).[1] **2,3-*syn*-5b**: ^1H NMR (250 MHz, $CDCl_3$ with 1% formic acid) δ 3.86 (m, 1H), 3.71 (s, 3H), 2.58 (pseudo quint, $J \approx$ 7.0 Hz, 1H), 1.50 (m, 2H), 1.30 (s, 1H), 1.21 (d, J = 7.3 Hz, 3H), 0.96 (t, J = 7.3 Hz, 3H). **2,3-*anti*-5b**: ^1H NMR (250 MHz, $CDCl_3$ with 1% formic acid) δ 3.71 (s, 3H), 3.64 (m, 1H), 2.58 (pseudo quint, $J \approx$ 7.0 Hz, 1H), 1.50 (m, 2H), 1.25 (br s, 1H), 1.18 (d, J = 7.3 Hz, 3H), 0.98 (t, J = 7.4 Hz, 3H).

Methyl 4-(Benzyloxy)-3-hydroxy-2,4-dimethylpentanoate (2,3-*syn*- and -*anti*-5c): IR (thin film) 3459, 3064, 2977, 2948, 2880, 1726, 1455, 1370, 1197, 1061, 741, 710 cm^{-1}. Anal. Calcd for $C_{15}H_{22}O_4$: C, 67.65; H, 8.33. Found: C, 67.84; H, 8.39.

2,3-*syn*-5c: ^1H NMR (250 MHz, $CDCl_3$) δ 7.31 (m, 5H), 4.45 (s, 2H), 3.86 (t, J = 6.2 Hz, 1H), 3.57 (s, 3H), 2.76 (pseudo quint, $J \approx$ 6.9 Hz, 1H), 2.55 (d, J = 6.2 Hz, 1H, *syn*-OH), 1.34 (s, 6H), 1.27 (d, J = 6.8 Hz, 3H); ^{13}C NMR (62.5 MHz, $CDCl_3$) δ 176.1, 138.9, 128.1, 127.5, 127.2, 77.9, 76.6, 63.7, 51.4, 38.3, 22.5, 21.2, 13.7 (*syn*-2-CH_3). **2,3-*anti*-5c**: ^1H NMR (250 MHz,

(12) The use of optically pure (*S*)-ethylenebis(H_4Ind)$_2$Zr(OTf)$_2$[3] as a catalyst with simple aldehyde substrates gave rise to aldol products in <20% ee. Collins, S. Unpublished results.

(13) ^{13}C NMR spectra of mixtures of $Cp_2Zr(OTf)_2$ and aldehyde **1a** in CD_3NO_2 at −30 °C revealed the presence of two sets of signals due to free and bound **1a**. However, it was not possible to unambiguously determine the binding mode (i.e., mono- vs bidentate) from these spectra.[5b]

(14) Alternatively, the use of enol silanes that give rise to less reactive silyl triflate intermediates should circumvent the Si-catalyzed pathway as shown for ^{n}BuMe$_2$SiOTf.

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(16) (a) Ainsworth, C.; Chen, F.; Kuo, Y. *J. Organomet. Chem.* **1972**, *46*, 59. (b) Ireland, R. E.; Mueller, R. H.; Willard, A. K. *J. Am. Chem. Soc.* **1976**, *98*, 2868.

(17) Kozikowski, A. P.; Stein, P. D. *J. Org. Chem.* **1984**, *49*, 2301.

(18) Stummp, M. C.; Schmidt, R. R. *Tetrahedron* **1986**, *42*, 5941.

$CDCl_3$) δ 7.31 (m, 5H), 4.43 (d, J_{AB} = 10.8 Hz, 1H), 4.37 (d, J_{AB} = 10.8 Hz, 1H), 3.68 (dd, J = 6.9, 3.4 Hz, 1H), 3.27 (s, 3H), 2.84 (pseudo quint, $J \approx 7$ Hz, 1H), 1.58 (d, J = 3.4 Hz, 1H, *anti*-OH), 1.31 (s, 6H), 1.27 (d, J = 6.8 Hz, 3H); ^{13}C NMR (62.5 MHz, $CDCl_3$) δ 176.7, 139.0, 128.0, 127.3, 127.1, 81.2, 77.1, 64.0, 51.1, 41.2, 21.8, 21.7, 16.8 (*anti*-2-CH_3).

Methyl 5-(Benzyloxy)-3-hydroxy-2,4,4-trimethylpentanoate (2,3-*syn*- and -*anti*-5d): IR (thin film) 3484, 2926, 2876, 1728, 1434, 1263, 1095, 1024, 804, 699 cm^{-1}. Anal. Calcd for $C_{16}H_{24}O_4$: C, 68.55; H, 8.63. Found: C, 68.55; H, 8.49.

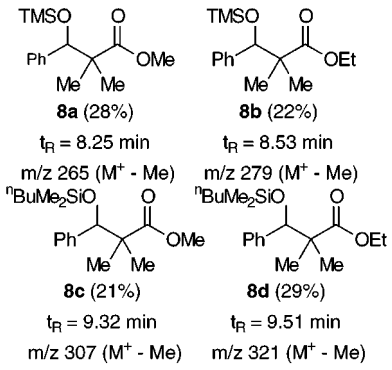
2,3-*syn*-5d: ^{1}H NMR (250 MHz, $CDCl_3$) δ 7.32 (m, 5H), 4.51 (s, 2H), 3.87 (d, J = 5.1 Hz, 1H), 3.67 (s, 3H), 3.51 (d, J_{AB} = 8.6 Hz, 1H), 3.45 (d, J_{AB} = 8.6 Hz, 1H), 2.65 (pseudo quint, $J \approx 6.7$ Hz, 1H), 1.44 (s, 1H), 1.25 (d, J = 7.0 Hz, 3H), 0.94 (s, 6H); ^{13}C NMR (62.5 MHz, $CDCl_3$) δ 176.7, 137.7, 128.3, 127.4, 127.2, 79.7, 76.9, 73.5, 51.5, 41.5, 39.1, 22.7, 20.2, 13.3 (*syn*-CH_3). **2,3-*anti*-5d**: ^{1}H NMR (250 MHz, $CDCl_3$) δ 7.32 (m, 5H), 4.48 (s, 2H), 3.89 (d, J = 4.1 Hz, 1H), 3.62 (s, 3H), 3.34 (d, J_{AB} = 8.9 Hz, 1H), 3.25 (d, J_{AB} = 8.9 Hz, 1H), 2.77 (pseudo quint, $J \approx 7.2$ Hz, 1H), 1.60 (s, 1H), 1.33 (d, J = 7.2 Hz, 3H), 0.90 (s, 6H); ^{13}C NMR (62.5 MHz, $CDCl_3$) δ 177.3, 138.3, 128.1, 127.6, 127.3, 79.6, 76.5, 73.1, 51.4, 39.6, 39.0, 22.1, 20.6, 17.7 (*anti*-CH_3).

Methyl 3-Hydroxy-2,4,4-trimethylpentanoate (2,3-*syn*- and -*anti*-5e).[1] **2,3-*syn*-5e**: ^{1}H NMR (250 MHz, $CDCl_3$) δ 3.69 (s, 3H), 3.68 (d, J = 3.5 Hz, 1H), 2.76 (qd, J = 7.0, 3.5 Hz, 1H), 1.40 (br s, 1H), 1.25 (d, J = 7.0 Hz, 3H), 0.94 (s, 3H). **2,3-*anti*-5e**: ^{1}H NMR (250 MHz, $CDCl_3$) δ 3.69 (s, 3H), 3.28 (d, J = 2.0 Hz, 1H), 2.74 (qd, J = 7.0, 2.0 Hz, 1H), 2.08 (s, 1H), 1.35 (d, J = 7.0 Hz, 3H), 0.89 (s, 3H).

Isomerization of MeCH=C(OMe)(OTMS) to MeCH(TMS)CO_2Me. CD_3NO_2 was distilled from $CaCl_2$ and then dried for several days over powdered, activated, 4 Å molecular sieves. MeCH=C(OMe)(OTMS) (0.05 mmol, 8 mg, 9 μL) was added to a −29 °C CD_3NO_2 (0.70 mL) solution of $Cp_2Zr(OTf)_2$ (0.048 mmol, 25 mg), and ^{1}H NMR spectra were recorded. The formation of TMSOTf (δ 0.52 ppm, ca. 10 mol % of $Cp_2Zr(OTf)_2$ present) was evident from the first spectrum obtained. Isomerization was evident after 10 min at −29 °C from the appearance of signals at δ 3.6 (s, OMe), 2.2 (q, MeCH(TMS)−), 1.2 (d, MeCH(TMS)−), and 0.12 (s, TMS) at the expense of those due to **2** [δ 3.5 (overlapping s, OMe), 1.5 (overlapping d, MeCH=) and 0.24 (s, OTMS)]. This process was ∼50% complete after 50 min at −29 °C, while the amount of TMSOTf had increased about 3-fold and thereafter remained constant. In addition, a broadened peak at δ 6.5, present in the original spectrum, increased in intensity at the same rate as TMSOTf, reaching ca. 5−10 mol % of $Cp_2Zr(OTf)_2$ after 1 h. After 2 h of reaction, the isomerization was virtually complete and excess TMSOTf was deliberately added; this resulted in the disappearance of the signal at δ 6.5 ppm (see Figure S7 in the Supporting Information). At 0 °C in CH_3NO_2 solvent, the conversion of **2** to **4**, in the presence of $Cp_2Zr(OTf)_2$ (10 mol %), was complete after 2 h.

A similar study was conducted in dry CD_2Cl_2 in the presence of equimolar bis(triflate) catalyst. In this case, isomerization was not observed after 1−2 h at −30 °C, and only traces [<1 mol % based on $Cp_2Zr(OTf)_2$] of TMSOTf were present.

Reaction of Me_2C=C(OMe)($OSiMe_3$) (7a) and Me_2C=C(OEt)($OSiMe_2$Bu) (7b) with PhCHO. Me_2C=C(OMe)($OSiMe_3$) (0.5 mmol, 87 mg, 100 μL) and Me_2C=C(OEt)($OSiMe_2$Bu) (0.5 mmol, 115 mg, 131 μL) were added to a flask containing $Cp_2Zr(OTf)_2$ (0.05 mmol, 30 mg) in 2.0 mL of 2-nitropropane cooled to −78 °C. Benzaldehyde (1.2 mmol, 128 mg, 122 μL) was added in one portion to the cold flask, and the solution was stirred for 1 h. Aqueous buffer (pH 7, 100 μL) was added rapidly via syringe, the suspension was diluted with dry hexane (10 mL), and the suspension was allowed to warm to room temperature. The suspension was filtered through a Florisil plug, and the solvent was then removed in vacuo. A dilute solution was made up in ether, and GC−MS analysis revealed the presence of four products in the following relative amounts:



The GC peaks were assigned on the basis of the ($M^+ - 15$) peak (the parent ion was absent in all cases) as well as expected fragmentation patterns.

Similar experiments with TMSOTf and $Cp_2Zr(OTf)_2$ were conducted in CH_2Cl_2 at the same temperature. After 4 h, the reactions were quenched and analyzed in the same fashion (GC−MS data is summarized in the Supporting Information).

Preparation of Zirconocene 10. A solution of *anti*-**5e** (prepared from the lithium enolate of methyl propionate and pivaldehyde; anti/syn ∼15:1 after chromatography) in toluene (1.0 mmol in 1.0 mL) was added via syringe to a solution of Cp_2ZrMe_2 in toluene (1.0 mmol in 2.0 mL) at 0 °C. The syringe was rinsed with 3 × 0.5 mL of toluene, which was added to the mixture. The solution was warmed to room temperature and was stirred at this temperature until methane evolution ceased (ca. 10−15 min). The solvent was removed in vacuo to provide crude **9** as a pale oil that was sufficiently pure (^{1}H NMR spectroscopy) for further use: ^{1}H NMR (250 MHz, C_6D_6) δ 5.87 (s, 5H), 5.79 (s, 5H), 4.04 (d, J = 3.4 Hz, 1H), 3.41 (s, 3H), 2.54 (qd, J = 7.0, 3.4 Hz, 1H), 1.11 (d, J = 7.0 Hz, 3H), 0.82 (s, 9H), 0.33 (s, 3H).

A solution of **9** in diethyl ether (ca. 1.0 mmol in 2.0 mL) was cooled to −90 °C (ether, liquid N_2). A solution of triflic acid in diethyl ether (0.50 M) was cooled to the same temperature. Two mL (1.0 mmol) of this solution was added to the solution of **9** via precooled syringe with vigorous stirring. Methane evolution was rapid, and the mixture was warmed to 0 °C and kept at this temperature for 30 min. The solvent was removed in vacuo at 0 °C to provide compound **10** as a white solid, substantially pure by ^{1}H NMR spectroscopy: ^{1}H NMR (250 MHz, C_6D_6, 25 °C) δ 6.15 (br s, 5H), 6.04 (br s, 5H), 4.14 (d, J = 3.0 Hz, 1H), 3.35 (s, 3H), 2.46 (qd, J = 7.0, 3.0 Hz, 1H), 1.02 (d, J = 7.0 Hz, 3H), 0.78 (s, 9H). The ^{1}H NMR spectra of this material in CD_2Cl_2 at various temperatures are depicted in Figure 2.

Reaction of Complex 10 with TMSOTf. A solution of complex **10** (17 mg, 0.032 mmol) in dry CD_3NO_2 (0.60 mL) was prepared. A ^{1}H NMR spectrum of this solution was recorded at −29 °C. To the cold solution was added TMSOTf (5.9 μL, 0.032 mmol) via syringe. After the tube was briefly shaken, it was returned to the spectrometer probe; the first spectrum, obtained within 7 min after addition, revealed ca. 60% consumption of both **10** and TMSOTf, as revealed by integrals of relevant signals with respect to residual CD_2HNO_2, and the appearance of signals due to *anti*-**3e** and $Cp_2Zr(OTf)_2$. Spectra obtained after 20 and 35 min at −29 °C were recorded, and the results are summarized below:

t (s)	conversion (C)	C/1-C
420	0.586	1.415
1200	0.638	1.762
2100	0.675	2.078

A plot of C/1-C vs t was linear with a slope of 3.94×10^{-4} $s^{-1} = k[\mathbf{10}]_o$ and thus $k = 7.5 \times 10^{-3}$ M^{-1} s^{-1}.

Reaction of PhCHO and MeCH=C(OMe)(OTMS) Catalyzed by $Cp_2Zr(OTf)_2$ or TMSOTf. Solutions of PhCHO (0.40 mmol, 41 mg, 39 μL), MeC=C(OMe)(OTMS) (0.40 mmol, 64 mg, 74 μL), $Cp_2Zr(OTf)_2$ (0.020 mmol, 10 mg), and TMSOTf

(0.020 mmol, 5 mg, 4μL) were prepared in CD_2Cl_2 in 1.00 mL volumetric flasks. Into each of two NMR tubes was placed 0.70 mL CD_2Cl_2 along with 50 μL of the PhCHO solution and 10 μL of catalyst solution−TMSOTf in one tube and $Cp_2Zr(OTf)_2$ in the other. After each tube was cooled to −80 °C in a dry ice-filled dewar, the MeC═C(OMe)(OTMS) solution (50 μL) was added to the tube and it was immediately placed in the −80 °C probe of the NMR spectrometer. ^{1}H NMR spectra were gathered immediately and at various intervals during the reactions. With $Cp_2Zr(OTf)_2$ as catalyst the reaction had gone to completion (>95% conversion) before the first spectrum could be acquired (ca. 3 min).

In the case of TMSOTf, the reaction was slow enough to be followed by NMR at −80 °C. The first spectrum showed the conversion to be about 50%, but the reaction was not complete until ~20 min after addition. A small aldehyde resonance (δ 9.99 ppm) could be observed but its relative intensity did not change with time (or increased temperature), indicating that it was due to a slight excess of PhCHO in the reaction mixture. The effective rate constants k_{obs} were estimated, assuming second-order kinetics (first order in aldehyde and enol silane), using the time taken to reach ≥ 95% conversion and are summarized in eq 8.

Reaction of ^{t}BuCHO and MeCH═C(OMe)(OTMS) Catalyzed by $Cp_2Zr(OTf)_2$ or TMSOTf. Solutions of PhCHO (0.20 mmol, 22 μL in 0.25 mL CD_3NO_2, 0.80 M) and mesitylene (28 μL, 0.20 mmol, added as an internal standard in 0.125 mL CD_3NO_2, 1.60 M), MeC═C(OMe)(OTMS) (0.20 mmol, 37 μL in 0.25 mL CD_3NO_2, 0.80 M), $Cp_2Zr(OTf)_2$ (0.020 mmol, 12.2 mg in 0.125 mL CD_3NO_2, 0.16 M), and TMSOTf (0.040 mmol, 7.24 μL in 0.25 mL CD_3NO_2, 0.16 M) were prepared. Into each of two NMR tubes was placed 0.38 mL of solvent along with 80 μL each of the PhCHO and enol silane solution and 40 μL of the mesitylene solution to give a final concentration of aldehyde (or enol silane) of ca. 0.1 M. After recording a $t = 0$ spectrum at −30 °C, each tube was separately cooled to −30 °C in a dry ice/CH_3NO_2 filled Dewar, 4 μL of catalyst solution (i.e., 1 mol %) was added to the tube, and the tube briefly shaken and immediately placed in the −30 °C probe of the NMR spectrometer. ^{1}H NMR spectra were gathered immediately (i.e., within ~2−4 min of mixing) and at various intervals during the reactions. Both reactions were essentially complete in the time the first spectrum could be acquired.

Table 2. Reaction of Enol Silane 2 with tBuCH═O Catalyzed by TMSOTf and $Cp_2Zr(OTf)_2$

t (s)	[aldehyde]	[enol silane]	[TMSOTf]	[$Cp_2Zr(OTf)_2$]
		TMSOTf		
391	0.149	0.101	0.041	n/a
991	0.113	0.056	0.040	n/a
1591	0.103	0.045	0.040	n/a
2191	0.094	0.031	0.040	n/a
2791	0.088	0.026	0.039	n/a
		$Cp_2Zr(OTf)_2$		
0	0.160	0.158	n/a	0.030
736	0.091	0.093	0.026	0.029
1336	0.083	0.081	0.025	0.028
1936	0.061	0.063	0.025	0.028
2536	0.052	0.050	0.025	0.030
3136	0.048	0.047	0.025	0.030
3736	0.038	0.041	0.026	0.029

A similar procedure was followed in CD_2Cl_2 solution except the spectrometer and solutions were kept at −42 °C. The data obtained are plotted in Figure 1, while concentration data as a function of time are summarized in Table 2.

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Supporting Information Available: ^{1}H NMR spectra of various catalytic reactions, spectra of reaction of enol silane **2** with $Cp_2Zr(OTf)_2$, spectra of aldolate **10** and of its reaction with TMSOTf and GC−MS data for reactions of enol silanes **7a** and **7b** with PhCH═O in the presence of TMSOTf or $Cp_2Zr(OTf)_2$ (16 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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