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Homogeneous Catalysis. Mechanisms of the Catalytic Mukaiyama Aldol and Sakurai Allylation Reactions

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Abstract: The mechanisms of a number of Mukaiyama aldol and Sakurai allylation reactions catalyzed by the Lewis acids [Ti(Cp)$_2$(OTf)$_2$], Ph$_3$COTf, and Ph$_3$CClO$_4$ have been investigated. It is found that hydrolysis of the Lewis acid by trace amounts of water in the solvent can lead to the formation of acid. The acid then reacts with the silyl enol ether or allylic silane to generate Me$_3$SiOTf or Me$_3$SiClO$_4$, both of which are powerful catalysts for these reactions. Dehydration of the solvent or addition of a hindered base to quench the acid does not necessarily prevent the formation of these silyl catalysts. In the case of the [Ti(Cp)$_2$(OTf)$_2$] Lewis acid, Me$_3$SiOTf is generated as a consequence of the mechanism, and it is shown that all of the catalysis proceeds by the Me$_3$SiOTf species and that [Ti(Cp)$_2$(OTf)$_2$] acts only as an initiator for the production of Me$_3$SiOTf. For the case of the presumed Ph$_3$COTf catalyst, the Mukaiyama aldol reaction proceeds exclusively by the Me$_3$SiOTf catalyst and Ph$_3$COTf is neither an initiator nor a catalyst. It generates Me$_3$SiOTf by hydrolysis. It is shown that the rate and stereoselectivity of Me$_3$SiOTf catalysis depend on the concentration of triflate ions. The rate slows and the selectivity switches with an increase in triflate concentration. The rate of Sakurai catalysis of allylsilane with an acetal using Ph$_3$CClO$_4$ can be quantitatively accounted for by invoking only Me$_3$SiClO$_4$ catalysis. The Me$_3$SiClO$_4$ can be generated by hydrolysis, but when this is suppressed, Me$_3$SiClO$_4$ can be formed by allylation of Ph$_3$CClO$_4$. It is suggested that many of the reported catalysts may only be agents for the production of the real catalysts, namely, Me$_3$SiX species. The characteristics of Lewis acids which may obviate the intrusion of Me$_3$SiX catalysis are outlined.

Lewis acid induced reaction of a silyl enol ether with aldehydes and ketones (eq 1), an aldol cross-coupling reaction, is commonly referred to as the Mukaiyama reaction after the name of its discoverer.[1,2] The process involves carbon−carbon bond formation and the transfer of the silyl group from one oxygen atom to the other. The Mukaiyama reaction is an exceptionally mild method of carbon−carbon bond formation, and if the stereoselectivity of the reaction could be controlled, it would represent a powerful and versatile synthetic method, particularly since catalytic amounts of Lewis acid generally suffice. Subsequently, it was discovered that Lewis acids promoted the coupling of silyl enol ethers with acetals, ketals, and orthoesters. An analogous, but as yet less versatile, reaction was reported by Sakurai,[3] who found that Lewis acids promoted the reaction of allylic silanes with aldehydes, ketones, acetals, ketals, and orthoesters as illustrated in eqs 2 and 3.

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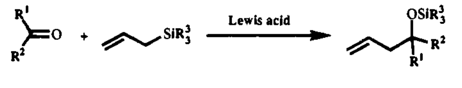

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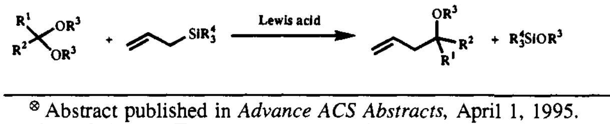

(3)

Initially stoichiometric amounts of Lewis acid were used to promote the Mukaiyama and Sakurai reactions, but it is now more common to employ catalytic loadings of the Lewis acid. There now exist a very large number of catalysts for these two reactions. Among these are the catalysts Me$_3$SiOTf,[4] Me$_3$SiI,[5] Me$_3$SiCl/SnCl$_2$,[6] Ph$_3$CCl/SnCl$_2$,[7] Ph$_3$CClO$_4$,[8] Ph$_3$COTf,[9] various rhodium complexes,[10] lanthanide triflates,[11] a variety of iron complexes,[12] complexes of Yb,[13] and complexes of Ti(IV)[14] for the Mukaiyama reaction. A similar, but less extensive, list of catalysts was also found for the Sakurai reaction.[3,15]

We have recently introduced three new transition metal based catalysts which were found to be very effective promoters of

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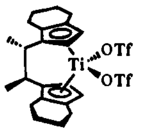
both the Mukaiyama and Sakurai reactions using very low catalytic loadings (~1 mol %). The three catalysts are [Ti(Cp)$_2$(OTf)$_2$],[16,17] [Zr(Cp)$_2$(OTf)$_2$(THF)],[16] and [Ru(salen)(NO)H$_2$O]SbF$_6$,[18] where Cp is the cyclopentadienyl ligand, OTf is CF$_3$SO$_3$$^-$, and salen is the ethylenediamine bisalicylate ligand which occupies planar positions about the octahedral ruthenium ion.[19] These catalysts were chosen in order to obviate some of the disadvantages that are encountered with conventional Lewis acids which include their sensitivity to water and their tendencies to rapidly redistribute ligands and to form oligomers. These characteristics of conventional Lewis acids present considerable problems in defining the structural origins of their stereoselective reactions. We demonstrated that the catalysts [Ti(Cp)$_2$(OTf)$_2$], [Zr(Cp)$_2$(OTf)$_2$(THF)], and [Ru(salen)(NO)H$_2$O]SbF$_6$ are insensitive to small amounts of water; the structures of these catalysts are defined and are readily elaborated for stereoselective transformations. The catalytic activity of these complexes depends on the oxophilic nature of the metals and on the lability of the OTf$^-$ and H$_2$O ligands which are replaced by the carbonyl oxygen of the substrate.[16,19] Upon coordination to the metal, the substrate becomes activated to react.

Having developed these new structurally defined metal-based Lewis acids, we prepared a number of chiral derivatives of the [Ti(Cp)$_2$(OTf)$_2$] catalyst. These are illustrated in **1**,[20] **2**,[21] and **3**.[22] All three of these catalysts were effective catalysts for the Mukaiyama, Sakurai, and Diels–Alder reactions. Catalyst **3** gave good enantioselectivity for certain Diels–Alder reactions,[23] but none of the catalysts gave any appreciable enantioselectivity for either the Mukaiyama or the Sakurai reaction using a variety of substrate combinations. Such results admit two possible explanations: either these catalysts are enantioselective for the Diels–Alder reaction, but are singularly ineffective for the enantioselective Mukaiyama and Sakurai reactions, or the mechanisms of the Mukaiyama and Sakurai reactions are not those commonly supposed. We suspected that the latter explanation was the correct one. This has led us to investigate the mechanisms of these reactions with the titanium and other catalysts. The results of our investigations are reported here, and the conclusions are significant for they present important challenges in designing stereoselective catalysts for these reactions.



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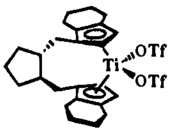

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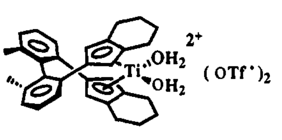

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Results

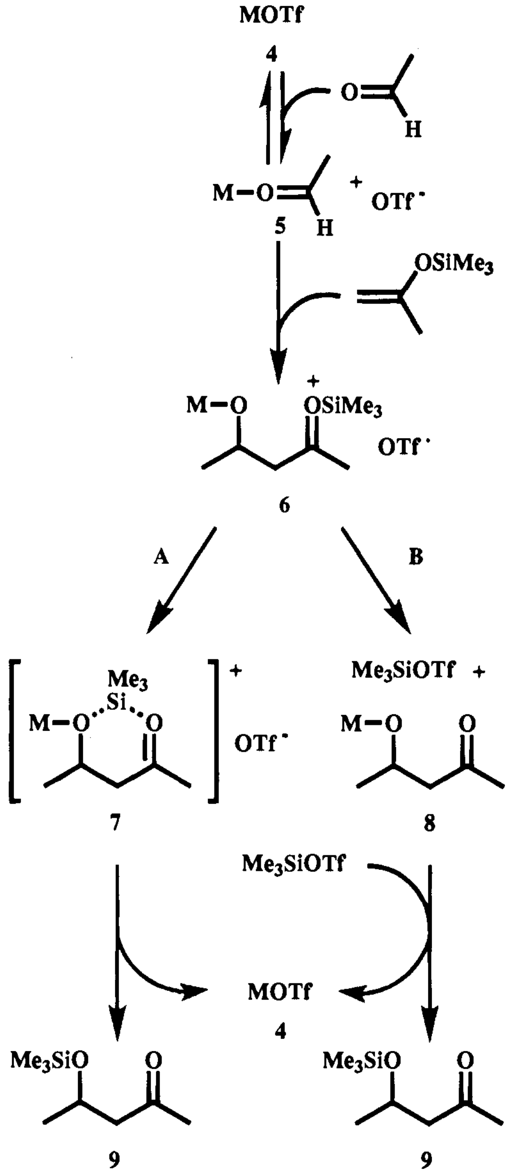

Figure 1. An outline of the two possible extreme mechanisms for the MOTf-catalyzed Mukaiyama reaction involving the reaction of an aldehyde with a silyl enol ether.

1. Possible Mechanisms. The two possible extreme mechanisms are illustrated in Figure 1, where the Mukaiyama reaction is used as an example and a Lewis acid triflate, MOTf, is employed as the catalyst. Reversible addition of the aldehyde to the Lewis acid **4** ⇌ **5** activates the aldehyde to attack by the silyl enol ether to produce an intermediate resembling **6**. At this stage the product can be formed either by a quasi-concerted path, A, or by a nonconcerted process, B. Path A involves the intramolecular transfer of the silyl group from the ketonic oxygen atom to the bound alkoxide oxygen, resulting in the formation of the product and the release of the catalyst. The nonconcerted path B leads to the formation of the aldolate intermediate **8** and Me$_3$SiOTf. For the regeneration of the catalyst and the formation of the product, the Me$_3$SiOTf is required to remove the alkoxide from intermediate **8** by an intermolecular process.

The two possible mechanistic paths A and B have distinctly different implications for enantioselective reactions. In the case of our chiral titanium complexes **1**, **2** and **3**, path A would be expected to give some enantioselection, particularly since **3** engenders chiral discrimination for the Diels–Alder reaction. Were path B the operative route, the possible enantioselection would depend on the relative rate of the step **8** → **9** versus the rate of (achiral) Me$_3$SiOTf catalysis. If the step **8** → **9** were very much faster than the rate of Me$_3$SiOTf catalysis, then the operation of either mechanism would be inconsequential to the

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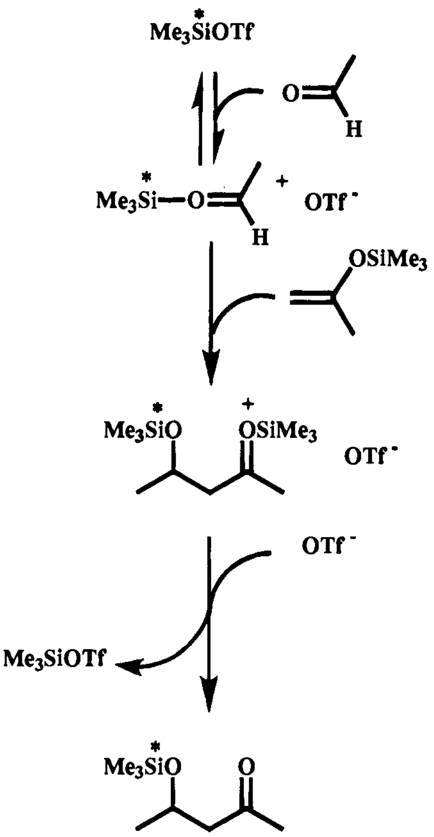


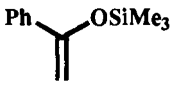
Figure 2. Proposed mechanism for Me_3SiOTf catalysis of the Mukaiyama aldol reaction. Note that the Me_3Si^+ group of the catalyst, designated by an asterisk, is retained in the product, and the Me_3Si^+ group of the silyl enol ether becomes the catalyst for the next cycle.

enantioselection since the mechanistic differentiation occurs after the enantioselective step (**5** → **6**). If Me_3SiOTf catalysis were comparable to or faster than step **8** → **9**, then most of the catalysis would proceed via the achiral Me_3SiOTf path and the chiral Lewis acid would serve only as an initiator for the production of the major or actual catalyst Me_3SiOTf.

If path B operates, the prospects for efficient asymmetric catalysis are bleak because Me_3SiOTf is an extraordinarily fast catalyst.[4] The reason for its efficiency is probably 2-fold: Me_3Si^+ is a very strong Lewis acid, but in addition, a degenerate catalytic cycle operates (Figure 2) which obviates the silyl transfer step. The most significant feature of the mechanism, illustrated in Figure 2, is that the silyl group of the catalyst remains in the product and that the silyl group of the silyl enol ether becomes the catalyst for the next catalytic cycle. In this way the interchange of silyl groups avoids the silyl transfer step and accelerates the turnover frequency. A further consequence of this mechanism is that chiral silyl triflates cannot be used as enantioselective catalysts because after the chiral catalyst is consumed in the product, catalysis proceeds by an achiral path involving the silyl group of the silyl enol ether.

2. $[Ti(Cp)_2(OTf)_2]$-Induced Catalysis. The above considerations provide a basis for a discussion of the mechanisms of the catalytic Mukaiyama and Sakurai reactions induced by the $[Ti(Cp)_2(OTf)_2]$ complex.[16,17] We found that Me_3SiOTf can be generated in a number of ways from the $[Ti(Cp)_2(OTf)_2]$ complex. The first method arises from the presence of trace amounts of water in CD_2Cl_2 even after the solvent has been dried over molecular seives and then distilled from CaH_2. Water may also enter the system from the substrates and from general manipulations in air. We find that after taking the usual, but not extreme, precautions trace amounts of water remain or enter the system.

Thus, when $[Ti(Cp)_2(OTf)_2]$ (~0.01 M) and the silyl enol ether **10** (~0.04 M) are dissolved in CD_2Cl_2 at 25 °C, an almost instantaneous set of reactions occur which produce acetophenone, Me_3SiOTf, $(Me_3Si)_2O$, and a Cp-containing titanium species which has a ^1H NMR signal at 6.43 ppm. The amounts



10

of acetophenone, Me_3SiOTf, and $(Me_3Si)_2O$ produced and the amount of $[(Ti(Cp)_2(OTf)_2]$ that remains depend on the amount of water present. The $[Ti(Cp)_2(OTf)_2]$ complex has low solubility in CD_2Cl_2, and we were able neither to lower the temperature nor to vary its concentration significantly. The amount of the species with a ^1H NMR signal at 6.43 ppm appears to vary somewhat with the initial concentration of $[Ti(Cp)_2(OTf)_2]$, but we have not been able to quantify the amounts accurately because of the solubility restrictions.

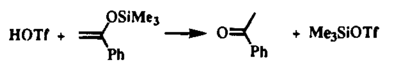
We interpret these observations by means of the reactions represented in eqs 4–10. The reactions represented by eqs 4–6 are likely to be rapid and reversible at 25 °C because the $[Ti(Cp)_2(OTf)_2]$ complex in the absence of **10** and when water is present in the CD_2Cl_2 solution shows only a single ^1H NMR signal (at 6.92 ppm). Reactions 5 and 6 produce triflic acid (HOTf). The triflic acid reacts with the silyl enol ether to give the corresponding ketone and Me_3SiOTf (eq 8); the latter then scavenges water to produce $(Me_3Si)_2O$ and regenerates HOTf. We have determined in separate experiments that reactions 8 and 9 are "instantaneous" even at −80 °C in CD_2Cl_2. It will be noted that HOTf catalyzes the dehydration of the solvent at the expense of the silyl enol ether. If all of the water were consumed to produce $(Me_3Si)_2O$, no HOTf nor Me_3SiOTf would remain (eq 10). We find, however, that Me_3SiOTf is present in solution and we therefore conclude that the Cp-containing titanium species with a ^1H NMR signal at 6.43 ppm is an oxo cluster[24] which has the stoichiometry $[Ti(Cp)_2O]$ (eqs 6 and 7). Consistent with this formulation is the fact that ^1H NMR integration shows that the ratio of "$[Ti(Cp)_2O]$" and Me_3SiOTf is 1:2 as would be predicted from the net eq 7 combined with eq 8. The $[Ti(Cp)_2O]$ complex is indefinitely stable in the presence of 2 equiv of Me_3SiOTf, indicating that the Me_3SiOTf reagent does not remove the oxo ligand during the time frame of our experiments. It will be noted that were Me_3SiOTf capable of removing the oxo ligand, the solution would be dry and no Me_3SiOTf nor HOTf would remain. We have used the monoaquo species for illustrative purposes, but it is clear the the overall conclusions are not affected if the diaquo species is included.

$$[Ti(Cp)_2(OTf)_2] + H_2O \rightleftharpoons [Ti(Cp)_2(OTf)(H_2O)]OTf \quad (4)$$

$$[Ti(Cp)_2(OTf)(H_2O)]OTf \rightleftharpoons [Ti(Cp)_2(OTf)(OH)] + HOTf \quad (5)$$

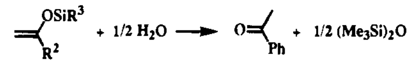
$$[Ti(Cp)_2(OTf)(OH)] \rightleftharpoons \text{"}[Ti(Cp)_2O]\text{"} + HOTf \quad (6)$$

$$\text{NET.}\quad [Ti(Cp)_2(OTf)_2] + H_2O \rightleftharpoons \text{"}[Ti(Cp)_2O]\text{"} + 2\,HOTf \quad (7)$$



$$HOTf + CH_2{=}C(OSiMe_3)Ph \longrightarrow O{=}C(CH_3)Ph + Me_3SiOTf \quad (8)$$

$$Me_3SiOTf + 1/2\,H_2O \longrightarrow 1/2\,(Me_3Si)_2O + HOTf \quad (9)$$



$$\text{NET.}\quad CH_2{=}C(OSiR^3)R^2 + 1/2\,H_2O \longrightarrow O{=}C(CH_3)Ph + 1/2\,(Me_3Si)_2O \quad (10)$$

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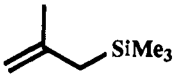
A wholly analogous set of reactions obtain when the allylic silane **11** (0.015 M) is added to a solution of $[Ti(Cp)_2(OTf)_2]$ (0.005 M) in CD_2Cl_2 at 25 °C. Upon mixing, isobutylene, Me_3SiOTf, $(Me_3Si)_2O$, and the $[Ti(Cp)_2O]$ species are detected. The ratio of $[Ti(Cp)_2O]$ to Me_3SiOTf is 1:2 as before. We interpret these results in terms of eqs 4−10 where the silyl enol ether is replaced by the allylic silane. Reactions analogous to eq 11 have been reported[25] to occur "instantaneously" at 25 °C.



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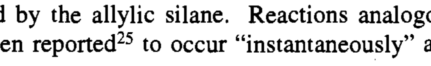
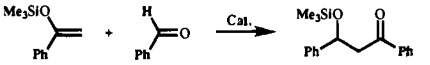


(11)

We have found that Me_3SiOTf is a very rapid catalyst for both the shown Mukaiyama (eq 12) and Sakurai (eq 13) reactions in CD_2Cl_2 at 25 °C. We also find that $[Ti(Cp)_2(OTf)_2]$ induces catalysis of these reactions, and since in the presence of even trace amounts of water Me_3SiOTf is formed, the question arises as to whether the Me_3SiOTf or $[Ti(Cp)_2(OTf)_2]$ or both are catalysts for the reaction when traces of water are present. This ambiguity can be resolved either by resorting to extreme measures to remove trace amounts of water or by neutralizing the HOTf which initiates the formation of Me_3SiOTf. We chose the latter strategy by employing the hindered base **12**.[26] Thus, for the Mukaiyama reaction (eq 12), the $[Ti(Cp)_2(OTf)_2]$ complex was dissolved in "dried" CD_2Cl_2 (0.01 M) at 25 °C followed by addition of an excess of base **12** (0.012 M), and then the silyl enol ether **10** (0.02 M) was added. Under these basic conditions ^1H NMR spectroscopy indicates that, in addition to the $[Ti(Cp)_2(OTf)_2]$ complex and the protonated and free base **12**, there exists ~2% (based on the titanium present) of two new Cp-containing titanium species with signals at 6.50 and 6.48 ppm. The ratio of these two species varies over a period of 2 h. These may be hydroxo-bridged species, but we have not identified them. No Me_3SiOTf was detected. This is consistent with our independently studied observation that the HOTf salt of **12** does not react with the silyl enol ether. When benzaldehyde (~0.02 M) is added to the solution of $[Ti(Cp)_2(OTf)_2]$, **12**, and silyl enol ether, the Mukaiyama reaction begins and after ~2 h the reaction is complete at 25 °C. As the reaction proceeds there appears in solution Me_3SiOTf and a titanium species which is identified as the aldolate intermediate **13** which is in equilibrium with the chelated form **14**. At 25 °C only a single, broad signal is observed for the Cp proton resonances, but upon cooling to −80 °C, both of the species **13** and **14** are resolved; the Cp proton resonances are diastereotopically split, and the aldolate proton resonances are sharp and distinct for each species. The ratio of the aldolate intermediate and Me_3SiOTf is 1:1 throughout the course of the reaction. After the reaction is ~90% complete, these two species have built up to their maximum concentrations. At this stage the aldolate **13** $\rightleftharpoons$ **14** represents about 25% of the total titanium concentration. When the reaction is complete, the aldolate **13** $\rightleftharpoons$ **14** remains in the presence of the Me_3SiOTf for over 15 h, indicating that the possible reaction between the two is very slow. The origins of the aldolate and of Me_3SiOTf are clearly connected with the mechanism of the reaction because addition of the Mukaiyama product (eq 12) to a solution of $[Ti(Cp)_2(OTf)_2]$ in CD_2Cl_2 at 25 °C produces neither the aldolate nor Me_3SiOTf.



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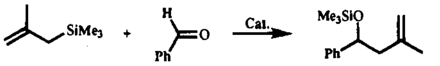

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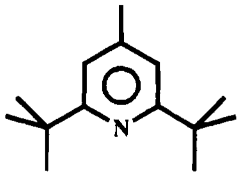

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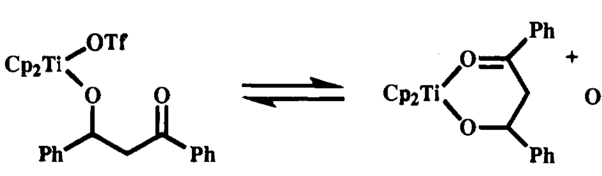
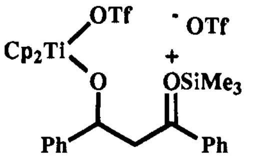


13 **14**

The mechanistic implications of these observations seem clear. In the presence of the base the benzaldehyde binds to the titanium by triflato displacement and the coordinated benzaldehyde couples with the silyl enol ether to produce an intermediate resembling **15**. The trimethylsilyl group is then captured by OTf^- to give Me_3SiOTf and the titanium aldolate. Since the aldolate is stable in the presence of Me_3SiOTf, all of the catalytic turnover occurs via Me_3SiOTf and the titanium complex serves only as an initiator for the production of the true catalyst Me_3SiOTf via an acyclic transition state.



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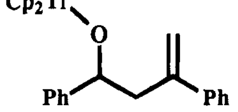
An almost identical course obtains for the Sakurai reaction (eq 13) under similar conditions. Thus, addition of the hindered base **12** (0.008 M) to a CD_2Cl_2 solution of $[Ti(Cp)_2(OTf)_2]$ (0.005 M) followed by the allylic silane **11** and benzaldehyde (both 0.015 M) at 25 °C results in reaction. After ~30 h, 90% of the reaction is complete. During this time we observed a gradual buildup of intermediate **16** and an equivalent amount of Me_3SiOTf. At 90% of reaction, these species reached their maximum concentrations and **16** constituted about 40% of the total titanium present. After the reaction is complete no reaction occurs between **16** and Me_3SiOTf after 65 h. The Sakurai allylic product (eq 13) does not react with $[Ti(Cp)_2(OTf)_2]$, and hence **16** and Me_3SiOTf arise from the mechanism of reaction. As in the case of the Mukaiyama reaction, we conclude that all of the Sakurai reaction occurs by Me_3SiOTf catalysis and that [Ti-



16

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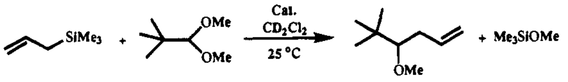
(25) Olah, G. A.; Husain, A.; Gupta, B. G. B.; Salem, G. F.; Narang, S. C. *J. Org. Chem.* **1981**, *46*, 5212. Morita, T.; Okamoto, Y.; Sakurai, H. *Synthesis* **1981**, 745.

(26) Cho, C. G.; Feit, B. A.; Webster, O. W. *Macromolecules* **1992**, *25*, 2081.

$(Cp)_2(OTf)_2]$ serves only as an initiator for the production of the true catalyst Me_3SiOTf via an acyclic transition state.

We have determined independently that Me_3SiOTf is indeed a catalyst for both the Mukaiyama and Sakurai reactions discussed here. Further, the rates of Me_3SiOTf catalysis are quantitatively consistent with the rates observed for the $[Ti(Cp)_2(OTf)_2]$-initiated reactions. The conclusions drawn here are similar to those reported for other catalysts.[27]

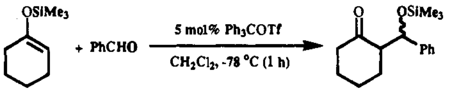
The $[Ti(Cp)_2(OTf)_2]$ complex promotes the coupling of allylic silanes with acetals, ketals, and orthoesters,[17] and we have briefly investigated one of these reactions to determine if $[Ti(Cp)_2(OTf)_2]$ is the true catalyst. For reasons of rate convenience the reaction shown in eq 14 was studied. In the absence of the hindered base, $[Ti(Cp)_2(OTf)_2]$ catalyzes this reaction, but small amounts of Me_3SiOTf were detected, probably arising from the hydrolysis of the titanium complex. We found that Me_3SiOTf is an effective catalyst for this coupling. When the reaction was performed in the presence of the hindered base employing the methods described earlier, no reaction was observed. Further, under these basic conditions no reaction occurred with allylsilane and the more electrophilic acetal $PhCH(OMe)_2$. These results imply that $[Ti(Cp)_2(OTf)_2]$ is neither a catalyst nor an initiator of this coupling. Rather, the small but constant amount of Me_3SiOTf detected in the reaction in the absence of base is the sole catalyst and arises from the reactions shown in eqs 4−7 and the analogue of eq 11. The last reaction should generate propene which was detected in proportion to the initial amount of water present.



(14)

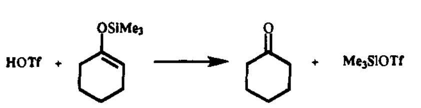
The results of these studies raise questions about the identity of the catalyst in the numerous examples of Mukaiyama and Sakurai catalytic reactions which have been reported. We have taken two examples from the literature for study, one a Mukaiyama aldol cross-reaction and the other a Sakurai reaction.

3. Trityl Triflate Promoted Mukaiyama Reaction. Mukaiyama reported[9] that trityl triflate (Ph_3COTf) catalyzed the aldol coupling shown in eq 15 for which the erythro/threo ratio (E:T) was reported to be 69:31. On closer study we discovered that the reaction was more complicated than that shown (eq 15). The catalytic reaction was followed by ^1H NMR spectroscopy using Ph_3COTf (0.001−0.003 M) in CD_2Cl_2 solution at −80 °C. The catalytic solution was found to contain Ph_3COH, $(Me_3Si)_2O$, Me_3SiOTf, and cyclohexanone in addition to Ph_3COTf, the substrates, and the product (E:T = 60:40). The concentrations of the first four species increased with the water content of the solution. The concentration of Ph_3COH was equal to that of Me_3SiOTf, and the amount of Me_3SiOTf was constant throughout the reaction. Addition of the silyl enol ether alone to a −80 °C CD_2Cl_2 solution of Ph_3COTf generated Ph_3COH, $(Me_3Si)_2O$, Me_3SiOTf, and cyclohexanone within the time of mixing. Thus, these species arise from the presence of water and are not a consequence of the mechanism of the Mukaiyama reaction. We conclude that these species arise from the sequence of reactions in eqs 16−18 which are reminiscent of those postulated for the $[Ti(Cp)_2(OTf)_2]$ system. We have confirmed independently that the reactions in eqs 17 and 18 occur instantaneously at −80 °C in CD_2Cl_2 solution by adding equivalent amounts of HOTf to the silyl enol ether at the concentration levels in question. The hydrolysis equilibrium (eq 16) was also studied independently, and it was found that in CD_2Cl_2 solution at 25 °C broad ^1H NMR signals were observed for the trityl resonances which become sharp at −80 °C, indicating that equilibration is rapid at 25 °C. Addition of the hindered base **12** to this solution at 25 °C slows the rate of equilibration as evidenced by the shape of the ^1H NMR signals, indicating that the exchange process is acid catalyzed. As noted previously (eqs 8−10) the reactions depicted in eqs 17 and 18 lead to a catalytic dehydration of the solution so that, if eq 16 were maintained as a rapid equilibration process, a completely dehydrated solution would result which would be devoid of Ph_3COH, Me_3SiOTf, and HOTf. The Ph_3COH species and an equivalent of Me_3SiOTf, however, remain during the time scale of catalysis. In the absence of acid no reaction between Me_3SiOTf and Ph_3COH (which would give Ph_3COTf, $(Me_3Si)_2O$, and HOTf) occurs over many hours in CD_2Cl_2 at −80 °C. Reaction does occur in the presence of HOTf. Thus, it appears that, under the conditions of catalysis, the rates of the reactions in eqs 17 and 18 are much faster than the acid-catalyzed reverse reaction shown in eq 16. The result is that all of the acid HOTf is consumed to leave the unreactive alcohol Ph_3COH and an equivalent of Me_3SiOTf.



(15)

$$Ph_3COTf + H_2O \rightleftharpoons Ph_3COH + HOTf \qquad (16)$$



(17)

$$Me_3SiOTf + 1/2\, H_2O \longrightarrow 1/2\, (Me_3Si)_2O + HOTf \qquad (18)$$

In order to identify the catalytic species, the catalysis was followed by ^1H NMR spectroscopy in CD_2Cl_2 at −80 °C under conditions where varying concentrations of Me_3SiOTf and Ph_3COTf were present. The rate of loss of benzaldehyde is

$$\frac{d[PhCHO]}{dt} = k[Cat][PhCHO][silyl\ enol\ ether] = k_{obs}[PhCHO][silyl\ enol\ ether]$$

where $k_{obs} = k[Cat]$. Linear plots were obtained by using the integrated form over at least 75% of reaction. A plot of k_{obs} versus [Cat] should give a linear dependence on catalyst concentration with zero intercept. Such a plot is shown in Figure 3 for varying concentrations of Ph_3COTf and of Me_3SiOTf. It is clear that within experimental error k_{obs} versus $[Me_3SiOTf]$ is linear with zero intercept, confirming that Me_3SiOTf is the sole catalyst. No correlation exists between k_{obs} and $[Ph_3COTf]$. Although it was reported[4] that the "Ph_3COTf" and Me_3SiOTf catalyst give almost the same E:T ratio, which is consistent with Me_3SiOTf being the catalyst in both cases, we were suspicious of the result because Mukaiyama[9] reported a dependence of the E:T ratio on the nature of the counterion. Thus, for example, with the present silyl enol ether, and with others, he found that the E:T ratio was reversed (33:67) when Ph_3CSbCl_6 was used instead of Ph_3COTf. If Ph_3CSbCl_6 is not the catalyst, as is probable, one is forced to conclude that Me_3SiOTf and $Me_3SiSbCl_6$ have different diastereoselectivities. We speculated that the reverse selection might be connected with ion-pairing effects involving the cationic $[Me_3Si{-}aldehyde]^+$ adduct and the anion. We have prepared pure Me_3SiOTf by reaction of HOTf with an excess of the silyl enol ether and by

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(27) Carreira, E. M.; Singer, R. A. *Tetrahedron Lett.* **1994**, *35*, 4323.

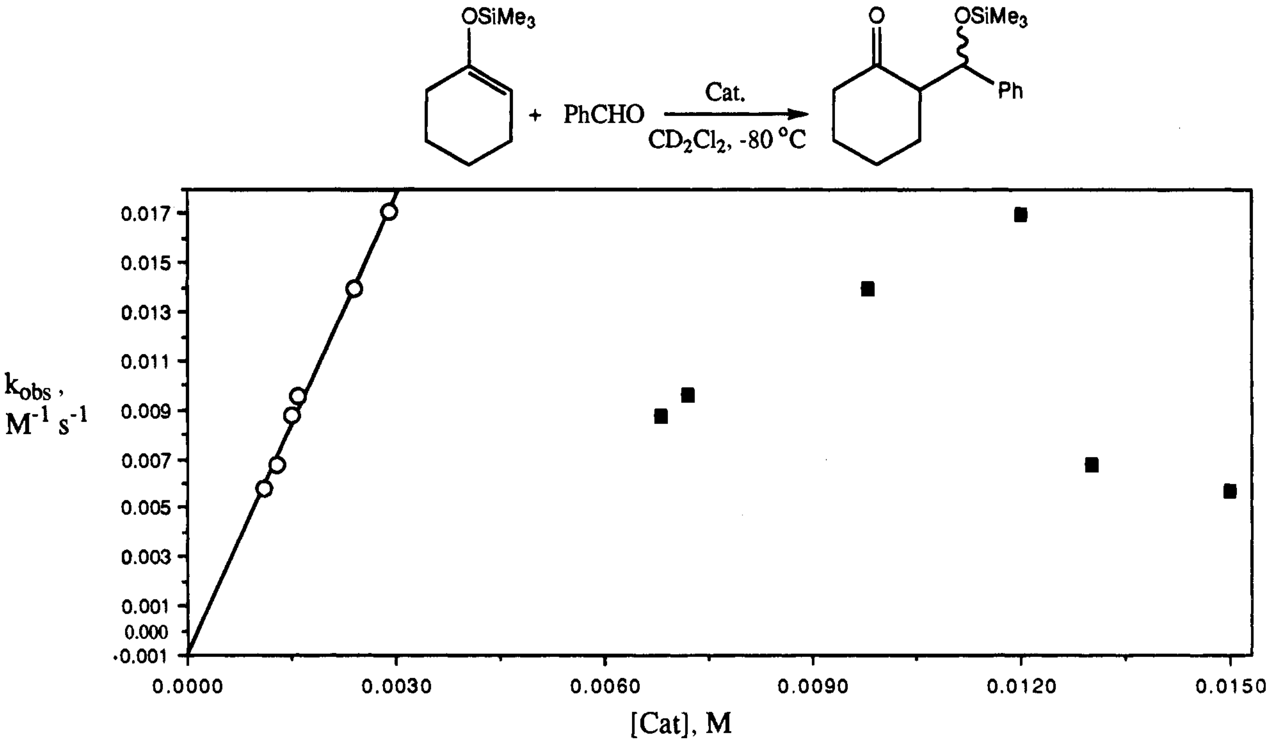


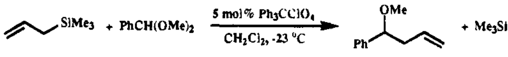
Figure 3. k_{obs} versus the concentrations of Me_3SiOTf (○) and Ph_3COTf (■) in the Mukaiyama aldol reaction.

double distillation from triethylamine. Using pure Me_3SiOTf, exceedingly rapid Mukaiyama catalysis occurs at a rate much faster than when Ph_3COTf is used. Under these conditions the E:T ratio is 30:70, which is the reverse of that reported by Mukaiyama using Ph_3COTf and by Hanaoko[4b] who used Me_3SiOTf. Addition of n-Bu_4NOTf to the solution of Me_3SiOTf followed by the silyl enol ether and benzaldehyde slowed the rate of catalysis and changed the E:T ratio, so that when sufficient OTf^- ions were added, the E:T ratio switched from 30:70 to close to that reported by Mukaiyama (69:31) using the Ph_3COTf-initiated reaction. Significantly, when the concentration of triflate ions was approximately equal to that present during the Ph_3COTf catalysis, Me_3SiOTf catalysis proceeded at about the same rate as that observed for the Ph_3COTf-initiated reaction and the E:T ratio was found to be similar, 55:45. The reduction in the rate of catalysis can, in part, be understood by the common ion effect where OTf^- competes with benzaldehyde for binding to Me_3Si^+. The precise reasons for the selectivity dependence on OTf^- ion concentration is less obvious to us except that we note that a cluster of triflate ions may surround the transition state and in some way control the selection. Whatever the explanation, the results elicit caution if attempts are made to define the origins of selection without recognizing ionic clusters which may influence the stereochemical outcome.

In order to confirm that Ph_3COTf was catalytically inactive, several additional experiments were performed. Since acid triggers the events illustrated in eqs 16–18 and is the catalyst for the production of Me_3SiOTf, addition of the hindered base **12** to a solution of Ph_3COTf should neutralize the acid and hence prevent the formation of Me_3SiOTf. We find that HOTf-protonated **12** does not catalyze the Mukaiyama reaction, and that it does not react with the silyl enol ether. Addition of the hindered base **12** to Ph_3COTf followed by the silyl enol ether of cyclohexanone and benzaldehyde did not induce the Mukaiyama aldol reaction after 2 h at −80 °C in CD_2Cl_2 solution. The absence of catalysis in the presence of sufficient hindered base is consistent with our conclusion that Ph_3COTf is not a catalyst.

Finally, we note that the conclusions drawn here for the Ph_3COTf-initiated catalysis of the silyl enol ether of cyclohexanone with benzaldehyde are different from those proposed previously,[28] where it was concluded that Ph_3COTf is the catalyst The previous study did not recognize the triflate ion dependence of the rate and selectivity nor the consequences of hydrolysis of the trityl ion.

4. Trityl Percholorate Promoted Sakurai Allylation. Mukaiyama[15c] reported that allyltrimethylsilane coupled with benzaldehyde dimethyl acetal in the presence of 5 mol % Ph_3CClO_4 (eq 19). Given the ineffectiveness of Ph_3COTf as a catalyst for the aldol cross-reaction, we were curious to discover whether Ph_3CClO_4 was the catalyst for this reported Sakurai catalysis. The catalysis was followed by ^1H NMR spectroscopy



(19)

in CD_2Cl_2 solution at −25 °C. The reaction was found to be complex, with a variety of reactions occurring in parallel with the catalysis. Since some of these reactions do not bear directly on the catalytic process, we will not mention them here. These parallel reactions are described in the Experimental Section. Using Ph_3CClO_4 (0.006 M) together with allylsilane and the acetal (both ~0.03 M) in CD_2Cl_2 solution at −25 °C, the reaction in eq 19 is complete in <5 min. In addition to the expected products (eq 19), the reaction contains $(Me_3Si)_2O$, Ph_3COMe, and ~1% propylene based on the initial concentration of allylsilane. The origins of Ph_3COMe and $(Me_3Si)_2O$ are discussed in the Experimental Section. No Me_3SiClO_4 could be detected, but it should be noted that under these conditions these methyl proton signals are broad. The propylene arises from the reaction of allylsilane with $HClO_4$ which, in turn, arises from the hydrolysis of Ph_3CClO_4 in a manner analogous to that discussed previously (eq 16). The presence of small amounts of propylene indicates that Me_3SiClO_4 is present below the level of detection.

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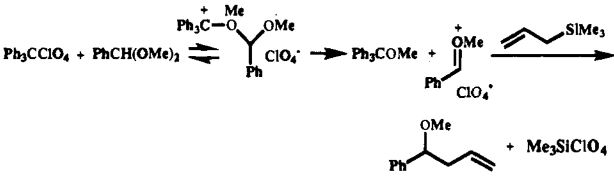
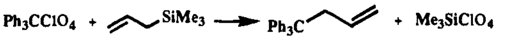
[28] Denmark, S. E.; Chen, C-T. *Tetrahedron Lett.* **1994**, *35*, 4327.

These observations leave the identity of the catalyst ambiguous; it could be Ph_3CClO_4, $HClO_4$, or Me_3SiClO_4. Since the last two are a consequence of hydrolysis of Ph_3CClO_4, the identity of the catalyst might be established by the use of the hindered base **12** as previously described for the other systems. Using the same concentrations and conditions as before and adding the base **12** before the substrates are added, the Sakurai catalysis (eq 19) still occurs but at a much slower rate. The reaction takes >2 h for completion as compared to <5 min in the absence of base. The final solution contains the Sakurai products together with the free and protonated base, Ph_3CClO_4, Ph_3COH, Ph_3COMe, and PhCHO. The last two products are produced by a parallel set of reactions and do not appear to be part of the Sakurai catalysis (see Experimental Section). No Me_3SiClO_4 nor propylene was detected during catalysis. The inability to detect Me_3SiClO_4 does not preclude it as a catalyst, however. In separate experiments the rate of Sakurai catalysis (eq 19) by Me_3SiClO_4 was measured in CD_2Cl_2 solution at −25 °C. From this data we calculate that the rate of catalysis using Ph_3CClO_4 in the presence of base can be accounted for by the presence of Me_3SiClO_4 in 7×10^{-5} M concentration. This concentration level is not readily detectable by ^1H NMR spectroscopy. Since the base is expected to quench the acid and indeed no propylene is detected when base is present, the question arises as to how, otherwise, Me_3SiClO_4 might be formed. We considered two possible reactions which are shown in eqs 20 and 21. The sequence illustrated in eq 20 assumes



(20)



(21)

that an oxocarbenium ion is formed[8b,29] by the trityl cation. Such a sequence would generate Ph_3COMe and Me_3SiClO_4. This mechanism requires that the Me_3SiClO_4 is capable of removing the methoxy group of Ph_3COMe, giving Me_3SiOMe and Ph_3CClO_4, to complete the catalytic cycle. We find that in acid media this methoxide exchange is rapid and reversible (eq 22) at 25 °C, where ^1H NMR line broadening is observed. In the

$$Ph_3COMe + Me_3SiClO_4 \overset{[H^+]}{\rightleftharpoons} Me_3SiOMe + Ph_3CClO_4 \quad (22)$$

presence of base, however, no methoxide exchange in either equilibrium direction occurs during the time scale of catalysis. Hence, catalysis cannot occur by a Ph_3CClO_4-induced carbenium ion mechanism. Further, Me_3SiClO_4 cannot be formed by the reverse of eq 22. At best Ph_3CClO_4 could act as an initiator for the formation of Me_3SiClO_4 (eq 20). This is unlikely because the amount of Me_3SiClO_4 should equal that of the detected Ph_3COMe and ^1H NMR spectroscopy would detect this concentration of Me_3SiClO_4. Whereas it is still possible that the oxocarbenium ion mechanism occurs, providing the necessary Me_3SiClO_4 below the level of detection, this need not be invoked since another source is known. The second possible source of Me_3SiClO_4 is illustrated in eq 21.[30] This is a relatively slow reaction at −25 °C in CD_2Cl_2 solution at the concentrations used here ([Ph_3CClO_4] = 0.003 M; [allylsilane] = 0.02 M). We find, however, that 25% reaction occurs after 5 h at −25 °C (pseudo-first-order $k = 1.8 \times 10^{-5}$ s^{-1}). Thus, after ~30 min there would be 7×10^{-5} M Me_3SiClO_4 present by this process during the Sakurai catalysis in the presence of base. The allylation reaction (eq 21) therefore can quantitatively account for all of the catalysis observed. Unless were were to invoke an improbable[31] cyclic concerted mechanism involving the trityl ion, the most plausible conclusion is that all of the catalysis proceeds by Me_3SiClO_4 which is generated by the allylation of the trityl ion.

5. Discussion. The present work serves to illustrate the difficulty of identifying the catalytic species in the Mukaiyama and Sakurai reactions. None of the three presumed catalysts $[Ti(Cp)_2(OTf)_2]$, Ph_3COTf, and Ph_3CClO_4 are the real catalysts. Trace amounts of water can generate "Me_3Si^+" species which are responsible for catalysis. Even when water is rigorously excluded, the supposed catalyst may serve only as an initiator for the production of Me_3Si^+ (path B, Figure 1), and in the case of allylic silanes, reaction with the Lewis acid can also lead to the production of Me_3Si^+. These observations are disconcerting for they call into question the nature of the true catalytic species in the numerous reported catalytic promoters of the Mukaiyama and Sakurai coupling reactions. It is our suspicion that many of these reported examples will be found to occur by Me_3Si^+ catalysis.

Although the problem seems to be systemic and pervasive, it may be amenable to solution based on the experiments reported here. The production of Me_3Si^+ initiated by hydrolysis of the Lewis acid can be suppressed by addition of the hindered base **12**. This simple procedure provides the first test in identifying the catalyst. The next question is to determine whether a concerted (path A, Figure 1) or nonconcerted (path B, Figure 1) path operates. This can be done either by identifying the Me_3Si^+ species by NMR spectroscopy or by crossover experiments.[24,31] The more interesting question, however, is to define the characteristics of the Lewis acid which will suppress catalysis by the Me_3Si^+ species. The alternative mechanisms illustrated in Figure 1 allow for a clear definition of the questions to be addressed. No Me_3Si^+ species will be formed if the Lewis acid induces a concerted reaction (path A). If a nonconcerted (path B) mechanism operates, then the rate of the removal of the aldolate (**8** → **9**) must be very much faster than catalysis by Me_3Si^+. This might be achieved by a number of means. First, if the Lewis acid does not release a counterion such as OTf^- or ClO_4^-, then the silyl group intermediate **6** is less likely to leave (**6** → **8**) by being stabilized by the counterion. Similarly polar coordinating solvents may also act to release a $Me_3Si{-}solvent^+$ species. Thus, by the use of neutral Lewis acids in noncoordinating solvents the intermediate **6** will be stabilized. With a more stable intermediate the catalysis may be induced to proceed by the concerted path. Diversion to the concerted path is likely to be enhanced if the M−O aldolate bond of intermediate **6** is weak. The strength of the M−O aldolate bond probably will correlate with the strength of the carbonyl bond in **5**. Thus, as a rough guide, Lewis acids which form weak M−O carbonyl bonds are likely to divert catalysis to the concerted path. It should be noted that mild Lewis acids promote the Mukaiyama aldol catalysis. Another possible method of avoiding the release of the Me_3Si^+ species is to incorporate into the Lewis acid ligands possessing groups which can capture the Me_3Si^+ species and are competent to transfer the silyl group to the aldolate. For example, carboxylic acid or ester functions may capture the Me_3Si^+ species and because of their proximity to the M−O aldolate bond may allow for facile transfer. This internal chaperoning of the Me_3Si^+ species may be crucial for the Sakurai reaction because the intermediate

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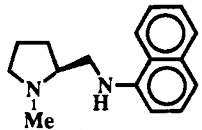
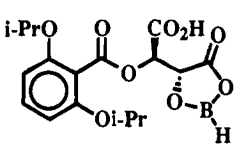
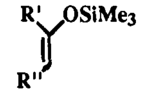
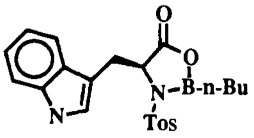
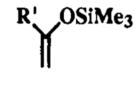
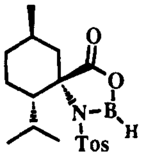
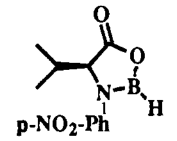
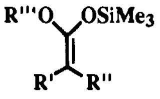
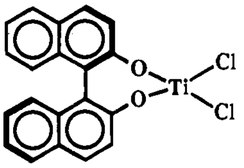
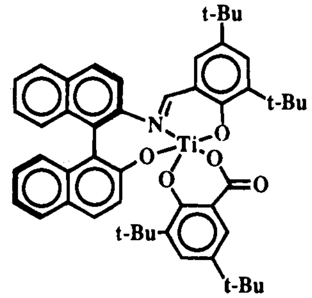
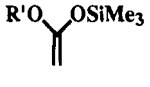
[29] Murata, S.; Suzuki, M.; Noyori, R. *Tetrahedron* **1988**, *44*, 4259. Sammakia, T.; Smith, R. S. *J. Am. Chem. Soc.* **1994**, *116*, 7915.

[30] Hagen, G.; Mayr, H. *J. Am. Chem. Soc.* **1991**, *113*, 4954.

[31] Mikami, K.; Matsukawa, S. *J. Am. Chem. Soc.* **1994**, *116*, 4077.

Table 1. Successful Asymmetric Catalysts for the Mukaiyama Aldol Reaction.

Entry	Catalyst	Mol%	Substrates	Temp (°C)	ee%	Comment	Ref.
1	 + $Sn(OTf)_2$	20	 RCHO	-78	77 - 98	slow addn. in EtCN	32a,b
2		20	 R' = R, OR RCHO	-78	76 - >95	in EtCN	32c,d
3		20	 RCHO	-78	86 - 93	in EtCN	32e
4		20	 X = O, S RCHO	-78	55 - 99	slow addn. in EtCN	32f,g
5		20	 RCHO	-78	60 - 97	in $EtNO_2$	32h
6		5	 RCHO	0	77 - >99	in toluene	31
7		2-5	 RCHO	-10	94 - 97	in Et_2O	32i

analogous to **6** is expected to be less stable than that for the Mukaiyama reaction. For the Sakurai reaction Lewis acids which undergo allylation with the allylic silane should be avoided (eq 21).

The validity of these prescriptions may be ascertained by considering the successful asymmetric catalysts which have been reported for the Mukaiyama aldol reaction. In order to achieve high enantioselectivity, catalysis must proceed via the chiral catalyst and the contribution to catalysis by the Me_3Si^+ species must be negligible. A selection of these chiral catalysts and relevant information are listed in Table 1.[31,32] In the present context a number of features associated with these catalysts should be noted. First, all were prepared *in situ* so that the structures of the catalysts, although plausible, have not been established. Second, aside from the catalyst in entry 1 all are neutral Lewis acids devoid of labile ligands which might capture Me_3Si^+. Third, entries 1−5 employ high catalyst loadings (20 mol %). Fourth, most employ solvents which are likely to form very weak adducts to Me_3Si^+. One of the significant features that leads to high enantioselectivity for entries 1 and 4 is the necessity of very slow addition of the substrates together with high catalyst loadings (20 mol %) which amounts to five turnovers. Although the precise turnover frequency is unknown,

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it is probable that by slow addition of substrates little or no turnover is achieved; rather five consecutive one-pot stoichiometric reactions are performed. We speculate the the necessity for slow addition arises from the formation of the achiral Me_3Si^+ catalyst and that the removal of the aldolate intermediate by Me_3Si^+ is a slow process. Were all of the substrates added at once the enantiomeric excess (ee) would be diminished because of Me_3Si^+ catalysis. Support for this supposition is provided by experiments which were reported for entry 1 where it was found that the ee decreased as the rate of substrate addition was increased. Using high catalyst loadings as in entries 1−5 will also tend to suppress the achiral Me_3Si^+ catalytic path. It is possible that the presence of carboxylate, either free or coordinated, and possibly toluenesulfonamido groups may serve to capture the Me_3Si^+ species so as to suppress the achiral path and, by proximity, to enhance the removal of the adolate. This possibility was recognized when the successful catalyst in entry 7 was devised. The catalyst in entry 6 is perhaps a special case where a concerted mechanism may operate. By use of double labeling experiments with the silyl enol ether, no crossover was detected during catalysis. The precise reasons for the probable concerted nature of catalysis by the catalyst in entry 6 cannot be ascertained until the structure of the catalyst is known. Consistent with our suggestion that nonpolar solvents will enhance the probability of a concerted process is the finding that the catalyst in entry 6 gives higher ee's in toluene solution than in the more polar solvent $EtNO_2$.

The results reported here demonstrate the complexity of devising chiral ctalysts for the Mukaiyama and Sakurai reactions. Although circumventing the Me_3Si^+ catalytic path is difficult, it is not impossible. The work presented here may provide a basis for future design of catalysts.

Experimental Section

General Information. ^{1}H NMR spectra were collected on a Varian XL 400 spectrometer in CD_2Cl_2 with $CHDCl_2$ (δ 5.32, t) as the internal standard; the chemical shifts are reported in parts per million (δ), and the multiplicities are reported as s (singlet), d (doublet), t (triplet), q (quartet), m (multiplet), and br (broad). The probe temperature was maintained using the built-in system and was uncorrected. Monitoring the samples by ^{1}H NMR spectroscopy quantitatively required special precaution. The T_1 for the Cp protons of $[Ti(Cp)_2(OTf)_2]$ was measured to be 22 s.[33] For this reason a delay time of 120 s was used between each acqusition, with a minimum of eight acquisitions obtained for each spectrum. NMR tubes and septa were oven-dried and placed in a vacuum desiccator for storage or placed in an inert (Ar) atmosphere glovebox. Syringes were air-dried and stored in a vacuum desiccator. All reactions were performed in dried (oven or vacuum desiccator) glassware and equipment and were manipulated under an atmosphere of Ar. Filtrations were performed using a 1.0 μm poly(tetrafluoroethylene) filter in a Nucleopore in-line filtration apparatus.

In experiments performed below room temperature it was critical that the solutions were maintained at the proper temperature. To this end CO_2/acetone (−78 °C) and CO_2/CCl_4 (−23 °C) cooling baths were used to maintain the temperature of the solutions during injection of substrates. In addition, substrates were required to be injected directly into the solutions using syringes equipped with long needles which were then spun to ensure proper mixing. The solution which was already in an NMR sample holder was then quickly removed and transferred into the precooled ^{1}H NMR probe.

CH_2Cl_2 was distilled from CaH_2 under nitrogen. CD_2Cl_2 obtained from Aldrich was refluxed over CaH_2 under Ar and then distilled into a pressure-equalizing dropping funnel with a condenser on top.

Hexamethyldisiloxane, cyclohexanone, and isobutylene were obtained from Aldrich and used to confirm peak assignments. Anhydrous silver perchloate was obtained from Alfa, and silver perchlorate monohydrate (used in some Ph_3CClO_4 preparations) was obtained from Aldrich. Triphenylmethyl chloride, triphenylmethanol, tetra-*N*-butylammonium trifluoromethanesulfonate, silver trifluoromethanesulfonate, 2,6-di-*tert*-butyl-4-methylpyridine, allyltrimethylsilane, 1-(trimethylsiloxy)cyclohexene, benzaldehyde, benzaldehyde dimethyl acetal, 1-phenyl-1-(trimethylsiloxy)ethylene, methoxytrimethylsilane, trimethylsilyl chloride, trimethylsilyl trifluoromethanesulfonate, and trifluoromethanesulfonic acid were obtained from Aldrich. For several of these, measures were taken to ensure their dryness and/or purity. Allyltrimethylsilane and 1-(trimethylsiloxy)cyclohexene were stored over 4 Å molecular sieves. Methoxytrimethylsilane was stirred over magnesium sulfate overnight and vacuum transferred prior to use. Benzaldehyde dimethyl acetal was stored over 4 Å molecular sieves or potassium carbonate. 1-Phenyl-1-(trimethylsiloxy)ethylene was used as received, or if not sufficiently dry it was placed over potassium carbonate. Trimethylsilyl trifluoromethanesulfonate was distilled from triethylamine under reduced pressure.[34] Trimethylsilyl chloride was distilled from CaH_2 under reduced pressure. Trifluoromethanesulfonic acid was distilled under reduced pressure. Benzaldehyde was distilled through a vacuum-jacketed Vigreux column under reduced pressure. Dicyclopentadienyltitanium bis(trifluoromethanesulfonate),[35] Ph_3COMe,[36] and pivalaldehyde dimethyl acetal[37] were prepared according to literature procedures. Dicyclopentadienyltitanium bis(trifluoromethanesulfonate), 2,6-di-*tert*-butyl-4-methylpyridine, and *n*-Bu_4NOTf were stored and weighed in an inert (Ar) atmosphere glovebox.

Preparations. Preparation of Triphenylmethyl Trifluoromethanesulfonate.[9] Triphenylmethyl chloride (0.600 g, 0.215 mmol) was dissolved in CD_2Cl_2 (0.4 mL), and then transferred onto solid AgOTf (0.0553 g, 0.215 mmol). This immediately produced a bright yellow solution, and a white powder was observed. The suspension was vigorously stirred in the dark for 2.5 h and then was filtered into a 1 mL volumetric flask and brought to volume. The volumetric flask was sealed with a septum which was wired on and wrapped with parafilm and stored at −20 °C. This stock solution was then used for catalysis. ^{1}H NMR spectroscopy always showed ~20% Ph_3COH due to adventitious water. ^{1}H NMR (25 °C): (Ph_3COTf) δ 8.30 (3 H, br s), 7.92 (6 H, br s), 7.70 (6 H, br s); (Ph_3COH) δ 7.38−7.22 (15 H, br s). Under these conditions the hydroxy proton is not observable, and the resolution of the Ph_3COTf signals is dependent upon the amount of water present. Upon addition of an excess of hindered base **12**, the ^{1}H NMR spectrum becomes more resolved: (Ph_3COTf) δ 8.30 (3 H, br pseudo-t), 7.92 (6 H, pseudo-t, J = 4 Hz), 7.70 (6 H, pseudo-d, J = 4 Hz); (Ph_3COH) δ 7.34 (15 H, m). ^{1}H NMR (−80 °C): (Ph_3COTf) δ 8.25 (3 H, tt, J = 7.5, 1.3 Hz), 7.87 (6 H, m), 7.63 (6 H, m); (Ph_3COH) δ 7.24 (9 H, m), 7.19 (6 H, m). Under these conditions the hydroxy proton is not observable.

Preparation of Triphenylmethyl Perchlorate.[38] Triphenylmethyl chloride (0.0575 g, 0.0206 mmol) was dissolved in 0.3 mL of CD_2Cl_2. This solution was transferred into a suspension of silver perchlorate (0.0426 g, 0.0205 mmol) in 0.3 mL of CD_2Cl_2. This suspension was stirred in the dark for 22 h and filtered into a 1 mL volumetric flask and brought to volume. The solution was sealed and stored at −20 °C prior to use. ^{1}H NMR spectroscopy always showed ~20% Ph_3COH due to adventitious water. ^{1}H NMR (−25 °C): (Ph_3CClO_4) δ 8.28 (3 H, tt, J = 7.5, 1.3 Hz), 7.90 (6 H, m), 7.69 (6 H, m); (Ph_3COH) δ 7.22−7.26 (15 H, m). Under these conditions the hydroxy proton is not observable.

Preparation of Trimethylsilyl Perchlorate.[39] Silver perchlorate (0.0473 g, 0.228 mmol) was suspended in 1.0 mL of CD_2Cl_2, and trimethylsilyl chloride (29.0 μL, 0.229 mmol) was added. No changes were observed immediately. The suspension was stirred in the absence of light for 19 h, after which a white powder was present in the pale yellow solution. It was filtered into a 1 mL volumetric flask and brought to volume, the flask was sealed, and the stock solution was stored at −20 °C prior use. ^{1}H NMR spectroscopy showed 40% (Me$_3$-

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$\mathrm{Si)_2O}$ due to adventitious water. ^{1}H NMR (−25 °C): ($\mathrm{Me_3SiClO_4}$) δ 0.49, (9 H, s); (($\mathrm{Me_3Si})_2O$) δ 0.04 (18 H, s).

Preparation of $\mathrm{CH_2C(CH_3)CH_2SiMe_3}$, 11. **11** was prepared according to a literature procedure.[30] After distillation the fractions which retained more than trace THF were redistilled through a Vigreux column. The final product as analyzed by ^{1}H NMR spectroscopy contained >92% silane and trace THF, and the remainder of the material was $\mathrm{CH_2C(CH_3)CH_2CH_2C(CH_3)CH_2}$.

Preparation of $\mathrm{PhC(O)CH_2CH(OSiMe_3)Ph}$. To a flask (5 mL) containing $[\mathrm{Ti(Cp)_2(OTf)_2}]$ (0.0028 g, 0.0059 mmol) $\mathrm{CH_2Cl_2}$ (1 mL) was added, and this was cooled in an ice bath. Benzaldehyde (105 μL, 1.03 mmol) was added followed by 1-phenyl-1-(trimethylsiloxy)ethylene (250 μL, 1.22 mmol). Upon addition of the silyl enol ether the clear red-orange solution became clear pale-yellow. The solution was stirred at 0 °C for 5 min, and then was transferred directly onto a Florisil column and eluted with $\mathrm{CH_2Cl_2}$. The solvent was removed in vacuo, and the crude product (302 mg, 98%) was chromatographed on deactivated silica gel (5% water added) with $\mathrm{CH_2Cl_2}$. The chromatographed product (251 mg, 81%) contained no silyl enol ether and only a trace of acetophenone. ^{1}H NMR (25 °C, $\mathrm{CD_2Cl_2}$): δ 7.95 (2 H, m, aromatic), 7.26−7.24 (8 H, m, aromatic), 5.36 (1 H, dd, *J* = 8.7 and 4.2 Hz, methine), 3.52 (1 H, dd, *J* = 15.6 and 8.7 Hz, diastereotopic methylene) 3.04 (1H, d, *J* = 15.6 and 4.0 Hz, diastereotopic methylene), −0.06 (9 H, s, trimethylsilyl).

Preparation of $\mathrm{PhCH(OSiMe_3)CH_2C(CH_3)CH_2}$. To a flask (5 mL) containing $[\mathrm{Ti(Cp)_2(OTf)_2}]$ (0.0050 g, 0.010 mmol) $\mathrm{CH_2Cl_2}$ (1.8 mL) was added. The silyl enol ether (440 μL, 2.50 mmol) was added followed by dropwise addition of benzaldehyde (260 μL, 2.56 mmol) over 30 s. The clear orange solution became clear yellow and warm to the touch. After stirring for 5 min the solution was transferred onto Florisil and eluted with $\mathrm{CH_2Cl_2}$. The solvent was removed in vacuo, and the crude product (0.56 g, 95%) was isolated. The isolated product contained trace benzaldehyde. ^{1}H NMR (25 °C, $\mathrm{CD_2Cl_2}$): δ 7.35−7.25 (5 H, m, aromatic), 4.78 (1 H, dd, *J* = 8.0 and 5.2 Hz, methine), 4.74 (1 H, m, vinyl), 4.65 (1 H, m, vinyl), 2.41 (1 H, ddd, *J* = 12.6, 8.0 and 1.0 Hz, diastereotopic methylene), 2.31 (1 H, m, diastereotopic methylene), 1.73 (3 H, m, methyl), 0.01 (9 H, s, trimethylsilyl).

Mechanistic Studies Using $[\mathrm{Ti(Cp)_2(OTf)_2}]$. Reaction of $[\mathrm{Ti(Cp)_2(OTf)_2}]$ with 1-Phenyl-1-(trimethylsiloxy)ethylene, 10. $[\mathrm{Ti(Cp)_2(OTf)_2}]$ (0.0028 g, 0.0059 mmol) was dissolved in $\mathrm{CD_2Cl_2}$ (600 μL) in an NMR tube. The solution was checked by ^{1}H NMR spectroscopy, revealing a single proton resonance at δ 6.92 (10 H, s). **10** (5 μL, 0.024 mmol) was added, and it was monitored by ^{1}H NMR spectroscopy. The first spectrum obtained revealed **10** (53%), and the remainder of the silyl enol ether had been converted to acetophenone, $\mathrm{(Me_3Si)_2O}$, and $\mathrm{Me_3SiOTf}$ (<2% based on injected silyl enol ether). In addition there was a new Cp resonance at δ 6.43 (10 H, s, <3% based on the Cp protons) which, upon integration, gives 1:2 ratio versus $\mathrm{Me_3SiOTf}$. This served as the basis for assigning the peak at δ 6.43 as $[\mathrm{Ti(Cp)_2O}]$. No further reaction is observed after 1 h.

Reaction of $[\mathrm{Ti(Cp)_2(OTf)_2}]$ with $\mathrm{CH_2C(CH_3)CH_2SiMe_3}$. $[\mathrm{Ti(Cp)_2(OTf)_2}]$ (0.0018 g, 0.0038 mmol) was dissolved in $\mathrm{CD_2Cl_2}$ (760 μL). ^{1}H NMR spectroscopy showed a single resonance at δ 6.92 (10 H, s, Cp). Addition of the allylsilane (2.0 μL, 0.011 mmol) led to the observation in the first obtainable spectrum (Δt = 17 min) that 80% of the allylsilane remained. The remaining 20% was $\mathrm{(Me_3Si)_2O}$ and isobutylene which was confirmed by adding authentic samples. In addition $\mathrm{Me_3SiOTf}$ (4% based on allylsilane) was present, and there was a new Cp resonance at δ 6.43 (10 H, s, ∼4% based on the Cp protons). No further reaction was observed after 2 h. The resonance at δ 6.43 and $\mathrm{Me_3SiOTf}$ were in a ratio of 1:2 based on integration. This lends further support to the assignment of the δ 6.43 signal as $[\mathrm{Ti(Cp)_2O}]$.

$[\mathrm{Ti(Cp)_2(OTf)_2}]$-Initiated Mukaiyama Aldol Catalysis in the Presence of the Hindered Base 12. $[\mathrm{Ti(Cp)_2(OTf)_2}]$ (0.0056 g, 0.012 mmol) and 2,6-di-*tert*-butyl-4-methylpyridine, **12** (0.0030 g, 0.015 mmol), were dissolved in $\mathrm{CD_2Cl_2}$ (1200 μL). ^{1}H NMR spectroscopy revealed, in addition to these two compounds, protonated **12** and two new Cp resonances, one at δ 6.50 which was slowly converted into another at δ 6.48. These are assumed to be titanium hydroxy or mixed oxo species. **10** (4.9 μL, 0.025 mmol) was added to this solution, and ^{1}H NMR spectroscopy revealed no reaction after 1 h. $\mathrm{Me_3SiOTf}$ and the titanium enolate were not observed. Benzaldehyde (2.4 μL, 0.024 mmol) was added, and the catalysis was monitored by ^{1}H NMR spectroscopy. The reaction reached 90% completion at 1$^3/_4$ h at which point the maximum concentration of **13** (**14**) was present. Continued monitoring of the reaction for a total of 13 h showed no reaction between **13** (**14**) and $\mathrm{Me_3SiOTf}$. Reaction with acetophenone present in **10** was not observed during catalysis. This solution was then cooled to −80 °C in order to better resolve the spectrum of **13** (**14**). ^{1}H NMR (25 °C): δ 6.40 (10 H, br s, Cp), 6.32 (1 H, dd, *J* = 6.6, 5.8 Hz, methine); aromatic signals overlapped those of the silylated product, and the remaining signals were not observable at 25 °C. But, upon cooling to −80 °C, two sets of peaks could be observed in a 1:1 ratio which were assigned to **13** and the corresponding chelate, **14**. ^{1}H NMR (−80 °C): all aromatic resonances overlapped the silylated product; (**14**) δ 6.68 (5 H, s, Cp), 6.60 (5 H, s, Cp), 6.13 (1 H, d, *J* = 9.6 Hz, methine), 4.37 (1 H, d, *J* = 18.9 Hz, diastereotopic methylene), 2.96 (1 H, dd, *J* = 10.3 and 18.4 Hz, diastereotopic methylene); (**13**) δ 6.39 (5 H, s, Cp), 6.31 (5 H, s, Cp), 3.59 (1 H, dd, *J* = 17.9 and 7.5 Hz, diastereotopic methylene), 3.23 (1 H, dd, *J* = 18.0 and 5.5 Hz, diastereotopic methylene); the remaining methine proton signal overlapped the other signals.

Reaction of $[\mathrm{Ti(Cp)_2(OTf)_2}]$ with the Mukaiyama Aldol Product. To a solution of $[\mathrm{Ti(Cp)_2(OTf)_2}]$ (0.0025 g, 0.0052 mmol) and the hindered base **12** (0.0022 g, 0.011 mmol) in $\mathrm{CD_2Cl_2}$ (600 μL) was added the Mukaiyama aldol product $\mathrm{PhC(O)CH_2CH(OSiMe_3)Ph}$ (0.002 98 g, 0.009 98 mmol). Monitoring by ^{1}H NMR spectroscopy showed no **13** (**14**) and no $\mathrm{Me_3SiOTf}$ after 5 h.

$[\mathrm{Ti(Cp)_2(OTf)_2}]$-Initiated Sakurai Allylation Catalysis in the Presence of the Hindered Base 12. $[\mathrm{Ti(Cp)_2(OTf)_2}]$ (0.0027 g, 0.0057 mmol) and the hindered base **12** (0.0018 g, 0.0088 mmol) were dissolved in $\mathrm{CD_2Cl_2}$ (1140 μL), and the Cp resonance at δ 6.50 was again observed to slowly convert to that at δ 6.48 as reported above in the Mukaiyama aldol catalysis. **11** (3.0 μL, 0.017 mmol) was added. ^{1}H NMR spectroscopy revealed no reaction of **11** after $^3/_4$ h. Benzaldehyde (1.7 μL, 0.017 mmol) was added, and the reaction was monitored by ^{1}H NMR spectroscopy for 66 h. The reaction reached 90% at ∼28 h. The maximum concentration of intermediate **16** was reached after 21 h. $\mathrm{Me_3SiOTf}$ was observed in a 1:1 ratio with **16**. The reaction was monitored for a total of 66 h, and no reaction between **16** and $\mathrm{Me_3SiOTf}$ was observed. ^{1}H NMR (25 °C): (**16**) δ 6.383 (5 H, s, Cp), 6.376 (5 H, s, Cp), 5.78 (1 H, dd, *J* = 7.6 and 6.0 Hz, methine), 4.59 (1 H, m, vinyl), 2.63 (1 H, m, diastereotopic methylene), 2.34 (1 H, m, diastereotopic methylene), 1.65 (3 H, m, methyl); the remaining vinyl proton signal overlapped signals from the silylated product.

Reaction of $[\mathrm{Ti(Cp)_2(OTf)_2}]$ with the Sakurai Allylation Product. $[\mathrm{Ti(Cp)_2(OTf)_2}]$ (0.0015 g, 0.0031 mmol) was dissolved in $\mathrm{CD_2Cl_2}$ (620 μL), the Sakurai allylation product $\mathrm{PhCH(OSiMe_3)CH_2C(CH_3)CH_2}$ (2.3 μL, 0.0091 mmol) was added, and the reaction was monitored by ^{1}H NMR spectroscopy for 45 min. No **16** was observed. Hydrolysis of the product was observed, and $\mathrm{Me_3SiOTf}$ (<1%) and $[\mathrm{Ti(Cp)_2O}]$ (<1%, δ 6.43) were also observed.

$\mathrm{Me_3SiOTf}$ Catalysis of the Mukaiyama Aldol Reaction. The maximum concentration of $\mathrm{Me_3SiOTf}$ observed during the titanium-initiated reaction reported above was used in this catalysis. Because the rate of catalysis is slowed by the presence of $\mathrm{OTf^-}$ ions, the $\mathrm{Me_3SiOTf}$ catalysis was performed with 2 equiv of *n*-$\mathrm{Bu_4NOTf}$ despite the fact that $[\mathrm{Ti(Cp)_2(OTf)_2}]$ is observed to be a nonelectrolyte in $\mathrm{CH_2Cl_2}$. The 2 equiv of $\mathrm{OTf^-}$ was added to determine the minimum $\mathrm{Me_3SiOTf}$ catalytic rate that might obtain when $[\mathrm{Ti(Cp)_2(OTf)_2}]$ is present. To *n*-$\mathrm{Bu_4NOTf}$ (0.0018 g, 0.0046 mmol) in $\mathrm{CD_2Cl_2}$ (700 μL) was added $\mathrm{Me_3SiOTf}$ (0.5 μL, 0.0026 mmol) and silyl enol ether (5.0 μL, 0.024 mmol). It was observed by ^{1}H NMR spectroscopy that 50% hydrolysis of the silyl enol ether had occurred, leaving 0.012 mmol of **10**. To this solution was added benzaldehyde (2.3 μL, 0.023 mmol), and the reaction was monitored by ^{1}H NMR spectroscopy. The reaction reached 95% completion in 50 min. Thus, $\mathrm{Me_3SiOTf}$ is capable of catalyzing this Mukaiyama aldol reaction at the rate presented above.

$\mathrm{Me_3SiOTf}$ Catalysis of the Sakurai Allylation. The maximum concentration of $\mathrm{Me_3SiOTf}$ observed during the titanium-initiated reaction reported above was used in this catalysis. *n*-$\mathrm{Bu_4NOTf}$ (0.0005 g, 0.0013 mmol) was dissolved in $\mathrm{CD_2Cl_2}$ (1610 μL), and $\mathrm{Me_3SiOTf}$

(0.5 μL, 0.0026 mmol) was added followed by allylsilane **11** (5.0 μL, 0.0028 mmol). The ^{1}H NMR spectrum revealed that 68% of the allylsilane remained, and isobutylene and $(Me_3Si)_2O$ were produced. To this solution was added benzaldehyde (2.5 μL, 0.025 mmol), and the catalysis was monitored by ^{1}H NMR spectroscopy. The reaction reached 70% at 6 h. Thus, Me_3SiOTf is capable of catalyzing this Sakurai allylation at the rates presented above for the $[Ti(Cp)_2(OTf)_2]$-initiated reaction. Repetition of this experiment without *n*-Bu_4NOTf resulted in 90% reaction in 45 min.

$[Ti(Cp)_2(OTf)_2]$-Initiated Sakurai Allylation Catalysis with Pivalaldehyde Dimethyl Acetal. $[Ti(Cp)_2(OTf)_2]$ (0.0022 g, 0.0046 mmol) was dissolved in CD_2Cl_2 (600 μL). Allyltrimethylsilane (2.3 μL, 0.015 mmol) was added. ^{1}H NMR spectroscopy showed that 57% of the allyltrimethylsilane remained. Propene and $(Me_3Si)_2O$ were the observed products. In addition, Me_3SiOTf and "$Cp_2Ti{=}O$" (δ 6.43) were detectable just above the noise level. Pivaldehyde dimethyl acetal (2.5 μL, 0.015 mmol) was added, and the catalysis was monitored by ^{1}H NMR spectroscopy. After 1 h 61% product had formed.

Attempted Sakurai Allylation of Pivalaldehyde Dimethyl Acetal Using $[Ti(Cp)_2(OTf)_2]$ in the Presence of the Hindered Base 12. $[Ti(Cp)_2(OTf)_2]$ (0.023 g, 0.0048 mmol) and the hindered base **12**, (0.0019 g, 0.0093 mmol) were dissolved in CD_2Cl_2 (600 μL). ^{1}H NMR spectroscopy revealed the protonated form of the hindered base **12** and the Cp resonances at δ 6.50 and 6.48. Allyltrimethylsilane (2.3 μL, 0.015 mmol) was added, and ^{1}H NMR spectroscopy revealed no hydrolysis products and no Me_3SiOTf. Pivalaldehyde dimethyl acetal (2.5 μL, 0.016 mmol) was added. ^{1}H NMR spectroscopy revealed no reaction had occurred after 1 h.

Attempted Sakurai Allylation of Benzaldehyde Dimethyl Acetal Using $[Ti(Cp)_2(OTf)_2]$ in the Presence of the Hindered Base 12. $[Ti(Cp)_2(OTf)_2]$ (0.0062 g, 0.013 mmol) and the hindered base **12** (0.0042 g, 0.020 mmol) were dissolved in CD_2Cl_2 (700 μL). Allyltrimethylsilane (2.3 μL, 0.015 mmol) was injected followed by benzaldehyde dimethyl acetal (2.5 μL, 0.017 mmol). The solution was monitored by ^{1}H NMR spectroscopy for 1.5 h. No allylation product was detected.

Mechanistic Studies Using Ph_3COTf. Kinetics of the Mukaiyama Aldol Reactions. The solution prepared as described below was monitored by ^{1}H NMR spectroscopy through at least two half-lives (75% reaction). The ^{1}H NMR signals at δ 0.10 (9 H) and δ 7.55 (2 H) were used to monitor 1-(trimethylsiloxy)cyclohexene and benzaldehyde, respectively. A plot of the natural logarithm of the ratio of the concentrations of these species obtained from the ratio of the ^{1}H NMR integrals versus time revealed a linear second-order plot. The concentrations of Ph_3COTf, Me_3SiOTf, and benzaldehyde were determined by comparison of their intergrals versus total added silane. These data were then used to extract the second-order k_{obs}. This experiment was repeated at varying concentrations of Ph_3COTf and Me_3SiOTf to obtain the data for the k_{obs} vs [Cat] plot ($k = 6\ M^{-2}\ s^{-1}$).

Ph_3COTf Initiation of the Mukaiyama Aldol Catalysis. Ph_3COTf (40 μL, ~0.2 M) was injected into an NMR tube containing CD_2Cl_2 (620 μL). This was cooled to −80 °C, 1-(trimethylsiloxy)cyclohexene (4.00 μL, 0.021 mmol) was injected, and ^{1}H NMR spectroscopy revealed that 83% of the silyl enol ether was present. The remainder had been hydrolyzed, producing cyclohexanone, 17% (which was not observed to undergo aldol reaction on the time scale of these catalyses), and Me_3SiOTf, 3%, and the remainder of the Me_3Si- group was present as $(Me_3Si)_2O$, 7%. In addition Ph_3COH was present in a 1:1 ratio with Me_3SiOTf. The amount of Ph_3COH remained unchanged after addition of the silyl enol ether. (See the Results for a full explanation of the reactions occurring.) The concentrations of these species did not change over several hours. Benzaldehyde (1.9 μL, 0.019 mmol) was then added, and the reaction was monitored by ^{1}H NMR spectroscopy. The amounts of cyclohexanone, Me_3SiOTf, Ph_3COTf, $(Me_3Si)_2O$, and Ph_3COH were observed to remain constant during catalysis. The aldol product was obtained in an E:T ratio of 60:40. ^{1}H NMR (−80 °C): (erythro) δ 5.13 (1 H, d, J = 5.1 Hz, methine), −0.06 (9 H, s, trimethylsilyl); (threo) δ 4.91 (1 H, d, J = 9.0 Hz, methine), −0.14 (9 H, s, trimethylsilyl).

Me_3SiOTf Catalysis of the Mukaiyama Aldol Reaction. 1-(Trimethylsiloxy)cyclohexene (5.5 μL, 0.028 mmol) was dissolved in CD_2Cl_2 (800 μL) and cooled to −80 °C. HOTf (0.5 μL, 0.0057 mmol) was added at −80 °C, and the first ^{1}H NMR spectrum obtained after ~13 min showed that the reaction was complete, producing the expected Me_3SiOTf and cyclohexanone. $(Me_3Si)_2O$ was also produced due to the presence of water. No further reactions occurred, and no aldol product from cyclohexanone was observed. (See the Results for an interpretation.) Benzaldehyde (2.9 μL, 0.028 mmol) was added, and the reaction was monitored by ^{1}H NMR spectroscopy. The reaction was complete in less than 15 min, and the aldol product was obtained in an E:T ratio of 30:70. Repetition of this experiment by addition of HOTf to a solution of the substrates resulted in identical observations. Use of distilled, commercially available Me_3SiOTf resulted in identical observations.

Me_3SiOTf Catalysis of the Mukaiyama Aldol Reaction in the Presence of Excess OTf^-. *n*-Bu_4NOTf (0.0032 g, 0.0082 mmol) dissolved in CD_2Cl_2 (650 μL) was cooled to −80 °C. Me_3SiOTf (0.3 μL, 0.0016 mmol) and 1-(trimethylsiloxy)cyclohexene (4.0 μL, 0.021 mmol) were added. ^{1}H NMR spectroscopy indicated that 20% of the silyl enol ether had hydrolyzed. Benzaldehyde (2.0 μL, 0.020 mmol) was injected, and the reaction was monitored by ^{1}H NMR spectroscopy as described in the Kinetics of the Mukaiyama Aldol Reactions. An E:T ratio of 55:45 was observed in the products, and the rate was close to that observed during the Ph_3COTf-initiated catalysis ($k = 5\ M^{-2}\ s^{-1}$ vs $6\ M^{-2}\ s^{-1}$).

Reaction of Protonated 12 with 1-(Trimethylsiloxy)cyclohexene and Benzaldehyde. The hindered base **12** (0.0022 g, 0.011 mmol) was dissolved in CD_2Cl_2 (800 μL), and HOTf (0.5 μL, 0.006 mmol) was added followed by injection of 1-(trimethylsiloxy)cyclohexene (5.7 μL, 0.029 mmol) at −80 °C. After 1.5 h ^{1}H NMR spectroscopy showed no reaction. Benzaldehyde (3.1 μL, 0.028 mmol) was added at −80 °C. After 3 h at −80 °C ^{1}H NMR spectroscopy showed no reaction. The solution was warmed to room temperature, and no reaction was observed after 55 h.

Attempted Catalysis of the Mukaiyama Aldol Reaction Using Ph_3COTf in the Presence of the Hindered Base 12. The hindered base **12** (0.0017 g, 0.0083 mmol) was dissolved in CD_2Cl_2 (600 μL), and Ph_3COTf (25 μL, 0.2 M) was added. This was cooled to −80 °C, and benzaldehyde (2.2 μL, 0.022 mmol) was injected followed by 1-(trimethylsiloxy)cyclohexene (4.0 μL, 0.022 mmol). After 2 h ^{1}H NMR spectroscopy showed no aldol product and no Me_3SiOTf.

Mechanistic Studies Using Ph_3CClO_4. Ph_3CClO_4 Initiation of the Sakurai Allylation Reaction. Ph_3CClO_4 (50 μL, 0.2 M) was added to CD_2Cl_2 (600 μL), the solution was cooled to −80 °C, and benzaldehyde dimethyl acetal (4.0 μL, 0.027 mmol) was injected. The initial ^{1}H NMR spectrum at −25 °C showed the formation of Ph_3COMe and benzaldehyde, but no Ph_3COH was detected. The acetal methoxy resonance was significantly broadened, and 85% of the initially injected acetal remained. After 1.5 h no further reaction had occurred. These observations are understood in terms of the reactions depicted in eqs 23−27. The consumption of Ph_3CClO_4 (eq 26) and water (eq 25) shifts the equilibrium represented by eq 23, thereby giving a dry solution without Ph_3COH. These equations imply a 1:2 ratio of benzaldehyde to Ph_3COMe (eq 27). The observed ratio was within experimental error of this value. The water-free solution was cooled to −80 °C, and allyltrimethylsilane (2.8 μL, 0.018 mmol) was injected. ^{1}H NMR spectroscopy after 7 min (−25 °C) showed complete consumption of the allylsilane. In addition to the expected products and excess of acetal, $(Me_3Si)_2O$, trace propylene (<1%), and Ph_3COMe were observed. No benzaldehyde or product from the reaction of benzaldehyde and allyltrimethylsilane was observed. No Me_3SiClO_4 was observed. Ph_3COMe was present before addition of the allylsilane and remained unchanged. The trace propylene is expected to arise in a manner analogous to that previously described (see eq 11). The equivalent amount of Me_3SiClO_4 that would be produced would not

$$Ph_3CClO_4 + H_2O \rightleftharpoons Ph_3COH + HClO_4 \tag{23}$$

$$PhCH(OMe)_2 + HClO_4 \rightleftharpoons PhCH(OMe)^+ClO_4^- + MeOH \tag{24}$$

$$PhCH(OMe)^+ClO_4^- + H_2O \rightleftharpoons PhCHO + MeOH + HClO_4 \tag{25}$$

$$2\,Ph_3CClO_4 + 2\,MeOH \rightleftharpoons 2\,Ph_3COMe + 2\,HClO_4 \tag{26}$$

$$\text{NET}\quad PhCH(OMe)_2 + H_2O + 2\,Ph_3CClO_4 \rightleftharpoons PhCHO + 2\,Ph_3COMe + 2\,HClO_4 \tag{27}$$

be observable under these conditions due to broadening. The formation of $(Me_3Si)_2O$ and consumption of benzaldehyde can be explained by the reaction of benzaldehyde with Me_3SiOMe (see eq 28).[40] The observed amount of $(Me_3Si)_2O$ is consistent with complete consumption of benzaldehyde via this pathway.

$$PhCHO + 2\,Me_3SiOMe \xrightarrow{H^+} PhCH(OMe)_2 + (Me_3Si)_2O \quad (28)$$

Ph_3CClO_4 Initiation of the Sakurai Allylation Catalysis in the Presence of the Hindered Base 12. The hindered base **12** (0.0021 g, 0.010 mmol) was dissolved in CD_2Cl_2 (600 μL), and Ph_3CClO_4 (40 μL, 0.2 M) was added. The solution was cooled to −25 °C, and $PhCH(OMe)_2$ (3.0 μL, 0.020 mmol) was added followed by allyltrimethylsilane (2.5 μL, 0.016 mmol). The catalysis was monitored by ^{1}H NMR spectroscopy and reached 85% reaction after 1.5 h. Kinetic analysis revealed $k_{obs} = 2 \times 10^{-2}\ M^{-1}\ s^{-1}$. The solution was observed to contain the hindered base **12** and its protonated form, Ph_3CClO_4, Ph_3COH, and the expected products of allylation. In addition there was a much slower formation of Ph_3COMe and benzaldehyde compared to the reaction in the absence of base.

Kinetics of the Trimethylsilyl Perchlorate Catalyzed Sakurai Allylation Reaction. A standard solution of Me_3SiClO_4 (10 μL, 0.2 M) was diluted in a 1 mL volumetric flask to give a 0.002 M solution. Me_3SiClO_4 (20 μL, 0.002 M) was diluted in CD_2Cl_2 (660 μL), and allytrimethylsilane (3.0 μL, 0.019 mmol) was added at room temperature to allow hydrolysis to go to completion. The solution was then cooled to −25 °C, and benzaldehyde dimethyl acetal was added. The catalysis was monitored by ^{1}H NMR spectroscopy, and analyzed as described below, $k = 270\ M^{-2}\ s^{-1}$.

Kinetics of the Sakurai Allylation Reactions. The solutions described above were monitored by ^{1}H NMR spectroscopy through at least two half-lives (75% reaction). The ^{1}H NMR signals at δ 3.26 (6 H, s, methoxy) and δ −0.03 (9 H, s, trimethylsilyl) were used to monitor benzaldehyde dimethyl acetal and allyltrimethylsilane, respectively. A plot of the natural logarithms of the ratio of the concentration of these species obtained from the ratio of the ^{1}H NMR integrals versus time revealed a linear second-order plot. The concentrations of Ph_3CClO_4 and benzaldehyde dimethyl acetal were determined by comparison of their integrals versus total added silane. These data could then be used to obtain the second-order k_{obs} values.

Reaction of Ph_3COMe with Me_3SiClO_4 in the Presence of the Hindered Base 12. The hindered base **12** (0.0017 g, 0.0083 mmol) was dissolved in CD_2Cl_2 (580 μL), and Me_3SiClO_4 (80 μL, 0.2 M) was added. Ph_3COMe (0.001 14 g, 0.004 16 mmol) was weighed into a separate NMR tube, and both were cooled to −25 °C. The solution of Me_3SiClO_4 and the hindered base **12** was transferred onto the solid Ph_3COMe which immediately gave a pale yellow solution. ^{1}H NMR spectroscopy showed 2% Ph_3CClO_4 which is believed to have arisen due to competitive trapping of $HClO_4$ from adventitious water by the hindered base **12** and Ph_3COMe. No further reaction occurred after 2 h.

Reaction of Ph_3COMe with Me_3SiClO_4. Ph_3COMe (0.001 37 g, 0.004 99 mmol) was dissolved in CD_2Cl_2 (580 μL). Me_3SiClO_4 (80 μL, 0.2 M) was injected at −80 °C, immediately producing a clear yellow solution. The solution was placed into a −25 °C NMR probe. The ^{1}H NMR spectrum after 13 min revealed complete conversion to Ph_3CClO_4. The excess of Me_3SiClO_4 and of Me_3SiOMe showed only a single broad Me_3Si- resonance at δ 0.3 and a broad methoxy resonance at δ 3.6.

Reaction of Ph_3CClO_4 with Me_3SiOMe in the Presence of the Hindered Base 12. The hindered base **12** (0.0018 g, 0.0088 mmol) was dissolved in CD_2Cl_2 (620 μL), and Ph_3CClO_4 (40 μL, 0.2 M) was added. The solution was cooled to −80 °C, Me_3SiOMe (0.6 μL, 0.0044 mmol) was added, and the resultant solution was placed into the NMR probe at −25 °C. ^{1}H NMR spectroscopy revealed no reaction after 1.5 h.

Kinetics of the Reaction of Ph_3CClO_4 with Allyltrimethylsilane in the Presence of the Hindered Base 12. The hindered base **12** (0.0027 g, 0.013 mmol) was dissolved in CD_2Cl_2 (620 μL), and Ph_3CClO_4 (40 μL, 0.2 M) was added. Allyltrimethylsilane (2.3 μL, 0.014 mmol) was added at −80 °C, and this solution was transferred into the NMR probe at −25 °C. The reaction had reached 25% completion after 5 h. The initial concentration of Ph_3CClO_4 (0.0036 M) was determined by integration of the signal at δ 7.90 (6 H, m, aromatic) against the total allyltrimethylsilane (0.022 M) integral at δ −0.03 (9 H, s, trimethylsilyl). The formation of allyltriphenylmethane was then monitored by integration of the signal at δ 3.40 (2 H) compared with Ph_3CClO_4. The concentration of allyltriphenylmethane was plotted assuming pseudo-first-order kinetics to reveal a straight line, $k = 1.8 \times 10^{-5}\ s^{-1}$. ^{1}H NMR (25 °C): (allyltriphenylmethane) δ 7.30−7.17 (15 H, m, aromatic), 5.62 (1 H, m, vinyl), 5.02 (1 H, m, vinyl), 4.92 (1 H, m, vinyl), 3.43 (2 H, m, methylene).

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(40) Noyori, R.; Murata, S.; Suzuki, M. *Tetrahedron* **1981**, *37*, 3899. Noyori reported that Me_3SiOTf catalyzed the reaction of aldehydes with Me_3SiOMe to give the corresponding acetals. We have found that, during the allylation of benzaldehyde dimethyl acetal catalyzed by Me_3SiClO_4 which produces Me_3SiOMe, benzaldehyde is converted to the acetal provided the hindered base **12** is not present, whereas in the presence of the hindered base **12**, no reaction between Me_3SiOMe and benzaldehyde occurs. The clear implication is that this reaction is acid catalyzed and that neither Me_3SiClO_4 nor Me_3SiOTf is the catalyst.