Titanocene(III) catalyzed homogeneous hydrosilation–hydrogenation of pyridines

John F. Harrod, Ronghua Shu, Hee-Gweon Woo, and Edmond Samuel

Abstract: The homogeneous catalytic hydrosilation–hydrogenation of pyridines is observed in the presence of Cp_2TiMe_2 (Cp = η^5-C_5H_5) and CpCp*$TiMe_2$ (Cp* = η^5-C_5Me_5) as catalysts and using $PhSiH_3$ or $PhMeSiH_2$ as the source of Si-H. Under appropriate conditions, and with appropriate ring-substitution, good yields of the *N*-silyldihydropyridine or *N*-silyltetrahydropyridine products are be obtained. Although complete saturation is not achieved with organosilane alone, carrying out the reaction under moderate H_2 pressures can give excellent yields of *N*-silylpiperidines. Under moderate pressures of H_2, $[Cp_2TiH]_2$ catalyzes rapid H–D exchange between H_2 and the 2- and 6-positions of C_5D_5N. Under the same conditions, only traces of hydrogenation are observed. This, together with the regioselectivity of 3-picoline hydrosilation–hydrogenation, leads to the conclusion that the key step in the reaction is probably addition of Ti-Si to C=N.

Key words: hydrosilation, hydrogenation, pyridines, dimethyltitanocene, catalysis.

Résumé : Lorsqu'on utilise du $PhSiH_3$ ou du $PhMeSiH_2$ comme source de Si-H, en présence de Cp_2TiMe_2 (Cp = η^5-C_5H_5) ou de CpCp*$TiMe_2$ (Cp* = η^5-C_5Me_5) comme catalyseurs, on peut observer une hydrosilation–hydrogénation catalytique homogène des pyridines. Dans des conditions appropriées et en présence de substituants appropriés, il est possible d'obtenir de bons rendements de *N*-silyldihydropyridines ou de *N*-silyltétrahydropyridines. Même si l'on n'arrive pas à obtenir une saturation complète avec l'organosilane seul, les réactions effectuées sous des pressions modérées d'hydrogène peuvent conduire à d'excellents rendements des *N*-silylpipéridines. Sous des pressions modérées d'hydrogène, le $[Cp_2TiH]_2$ catalyse un échange rapide de H–D entre le H_2 et les positions 2 et 6 du C_5H_5N. Dans les mêmes conditions, on n'observe que de traces d'hydrogénation. Ce résultat et la régiosélectivité de l'hydrosilation/hydrogénation de la 3-picoline nous amènent à conclure que l'étape clé de la réaction est probablement l'addition de Ti-Si sur la double liaison C=N.

Mots clés : hydrosilation, hydrogénation, pyridines, diméthyltitanocène, catalyse.

[Traduit par la Rédaction]

Introduction

Many catalytic and stoichiometric reactions of titanocene derivatives with Group 14 hydrides have been reported. These include the dehydropolymerization of silanes (1) and germanes (2), cross-dehydrocoupling of silanes with alcohols (3), amines (4), hydrazines (5), and acetylenes (6), hydrosilation of ketones (7), esters (8), imines (9), and olefins (10), reductive cyclization of eneones (11), and polymerization of acetylenes (12).

Catalytic hydrosilation of a variety of unsaturated substrates has been widely used for functionalization of silicon compounds (13) and polymers (14, 15) and in organic synthesis (7–10, 16–18). A large class of substrates, which have to date resisted attempts at homogeneous catalytic hydrosilation, are the highly resonance stabilized aromatics such as benzene, pyridine, pyrrole, and thiophene. In this paper we report the use of titanocene derivatives as catalysts for the first examples of homogeneously catalyzed hydrosilation–hydrogenation of pyridines.[3]

Received August 8, 2000. Published on the NRC Research Press Web site at http://canjchem.nrc.ca on July 19, 2001.

Dedicated to Professor Brian James on the occasion of his 65th birthday.

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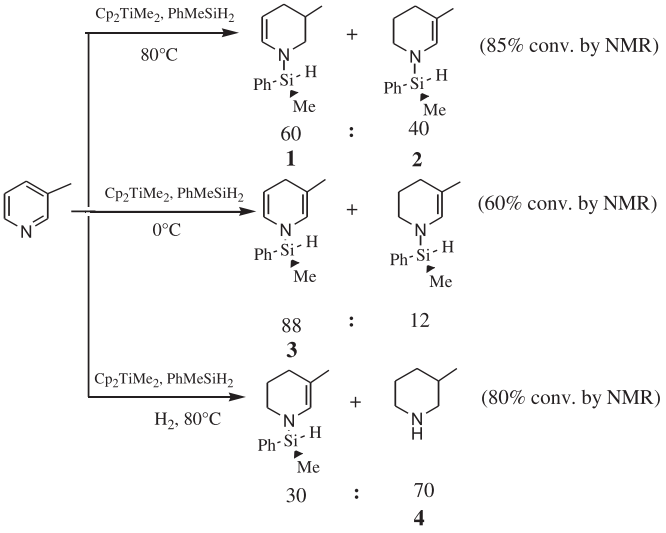
[3]A preliminary communication of this work has appeared, see ref. 19. Crystallographic data for **9a** and **10** (excluding structure factor tables) may be purchased from the Depository of Unpublished Data, Document Delivery, CISTI, National Research Council Canada, Ottawa, ON K1A 0S2, Canada. For information on obtaining material electronically go to http://www.nrc.ca/cisti/irm/unpub_e.shtml. Crystallographic information has also been deposited with the Cambridge Crystallographic Data Center as supplementary publication nos. CCDC 102516 (**9a**) and CCDC 102515 (**10**). Copies of the data are available free of charge from CCDC, 12 Union Road, Cambridge CB21EZ, U.K. (fax: +44 1223-336-033; e-mail: deposit@ccdc.cam.ac.uk).

 DOI: 10.1139/cjc-79-5/6-1075

Fig. 1. Reactions of 3-picoline.

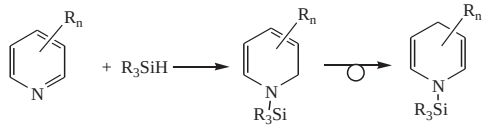


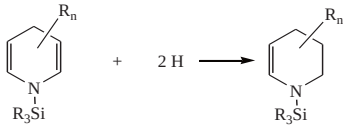
Results

Hydrosilation of pyridines in the presence of titanocene-derived catalysts

To our knowledge, pyridine is the only example of an aromatic substrate that has been successfully hydrosilated. A number of platinum group metals catalyze the addition of Me_3SiH to pyridine, with palladium being particularly effective (20). However, there is no report in the literature of a homogeneous catalytic hydrosilation of pyridine.

In the present work, both Cp_2TiMe_2 (Cp = η^5-C_5H_5) and CpCp*$TiMe_2$ (Cp* = η^5-C_5Me_5) were found to catalyze the hydrosilation–hydrogenation of pyridine, and a number of its derivatives, with $PhMeSiH_2$. Depending on the conditions, the reaction results in the addition of either Si-H, or Si-H and 2 additional atoms of H to the aromatic nucleus (eqs. [1] and [2]). The addition of more hydrogen to the primary diene product is expected in view of the known high catalytic activity of Cp_2TiMe_2 for hydrogen transfer from Si-H to certain olefinic substrates (21).

[1] 

[2] 

When the reaction is carried out at 80°C in the presence of Cp_2TiMe_2 with pyridine, or 4-picoline, the *N*-silyldihydropyridine intermediate is not observed, presumably because its hydrogenation occurs too rapidly. Under the same conditions 3,5-lutidine gives the *N*-silyl-1,4-dihydropyridine as the principal product, while 3,4-lutidine does not react.

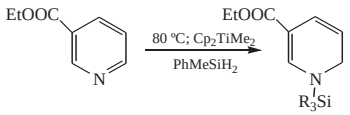
Even in the presence of a large excess of silane, the third double bond is not saturated, but reactions of pyridine, or 4-picoline, under a moderate pressure of H_2 (15–20 atm, 1 atm = 133.322 Pa) do result in complete saturation to give the respective *N*-silylpiperidines as the major products. Reaction of 3,5-lutidine under H_2 pressure gives substantial conversion to the *N*-silyl-1,2,3,4-tetrahydrolutidine, but none of the fully saturated product is produced.

The behavior of 3-picoline varies dramatically, depending on the reaction conditions. The three main reactions are summarized in Fig. 1. At 80°C, in the absence of H_2, the two *N*-silyltetrahydropyridine isomers, **1** and **2**, are the principal products. Under H_2, the **1**-isomer is fully saturated, while the **2**-isomer is unreactive.

Lowering the temperature both slows down the reaction steps and modifies the regioselectivity with respect to **1** and **2**. As the temperature is lowered, the rate of step [2] slows relative to step [1], resulting in ever-increasing amounts of the *N*-silyl-1,4-dihydro-3-picoline (**3**) relative to the tetrahydro-3-picolines, **1** and **2**. At the same time, the ratio of **1** to **2** progressively increases, until at 0°C **1** is no longer detectable. The influences of temperature on the products of the 3-picoline reaction are summarized in Table 1.

In general, the presence of a substituent at the 2- or 6-position shuts down the ring hydrosilation reaction. Thus, no hydrosilation was detected in reactions of $PhMeSiH_2$ with 2-picoline, 2,6-lutidine, 2-cyanopyridine, or 2,2′-bipyridine. An exception to this rule is quinoline, which undergoes reaction in the absence of additional H_2 to give a 3:1 mixture of *N*-phenylmethylsilyl-1,2,3,4-tetrahydroquinoline and *N*-phenylmethylsilyl-1,4-dihydroquinoline. Under moderate H_2 pressure, the only product isolated is *N*-phenylmethylsilyl-1,2,3,4- tetrahydroquinoline.

Hydrosilation of ethyl nicotinate (eq. [3]) gives a near-quantitative yield of *N*-phenylmethylsilyl-1,6-dihydro-3-carboethoxypyridine (**5**). The high selectivity for reduction

[3] 

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of the pyridine ring rather than the ester group is surprising, given the known high reactivity of esters towards hydrosilation under similar conditions (8). It should also be noted that the apparent regioselectivity in this case (1,6-addition) differs from that seen with 3-picoline and 3,5-lutidine (1,4-addition). However, given the high catalytic activity of the dimethyltitanocene–silane system for double bond migration (10), these products are more likely to be thermodynamically, rather than kinetically, determined.

An interesting reversal of selectivity is observed with ethyl isonicotinate (eq. [4]). In this case, the ester function is preferentially reduced, and no ring-hydrosilated products are observed. The major product (ca. 80%) under our standard conditions is **6**, in which the ester has been reduced to the alkoxide level. A significant amount (20%) of 4-picoline is also produced.

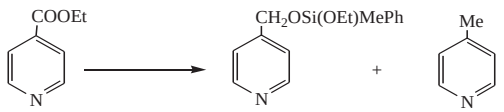
[4] 

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Table 1. Percentages of the products from hydrosilation–hydrogenation of 3-picoline under various reaction conditions.

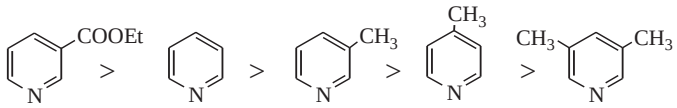
Temperature (°C)	*N*-(phenylmethylsilyl)-4-dihydro-3-picoline (**3**)	*N*-(phenylmethylsilyl)-2,3,4-tetrahydro-3-picoline (**1**)	*N*-(phenylmethylsilyl)-4,5,6-tetrahydro-3-picoline (**2**)
0	88	ND[a]	12
24	85	ND	15
50	27	17.2	56
60	19	27	49
80	3	57	39
80[b]	ND	ND	30

Note: All reactions run under standard concentration conditions of Cp_2TiMe_2:3-picoline:$PhMeSiH_2$ = 1:10:15. Concentrations determined by integration of ^1H NMR spectra.

[a]ND: not detected.

[b]Under 200 psi H_2, isolated yield. The blance of product in this case (70%) is 3-methylpiperidine (**4**).

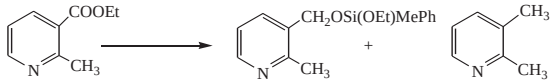
Scheme 1.



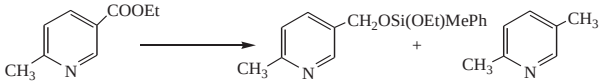
Relative rate	50	:	20	:	7	:	3	:	1
pK_a			5.58		5.70		5.99		6.15

Ring hydrosilation of ethyl nicotinate can be suppressed by substitution at the ring 2-, or 6-position. Thus, both ethyl 2-methyl- and ethyl 6-methyl-nicotinate hydrosilate exclusively at the ester function (eqs. [5] and [6]). Again, in both cases there is significant reduction to the alkoxide level products, **7** and **8**, and the respective lutidines. In the case of ethyl 2-methyl-nicotinate, the lutidine is the major product. No ring reduction products were detected by NMR spectrocopy. In all of the nicotinate and isonicotinate reactions, conversion of the reactant is quantitative by NMR.

[5]



[6]



Cp_2TiMe_2 is ineffective for the hydrosilation–hydrogenation of pyridine with $PhSiH_3$, or Ph_2SiH_2, because of competing Si-H–SiH dehydrocoupling reactions. The resulting oligophenylsilanes then hydrosilate the pyridine to give an intractable mixture of products. Neither *N*-silyldihydropyridine nor *N*-silylpiperidine products were detected by NMR in any of the $PhSiH_3$ reactions. The effectiveness of $PhMeSiH_2$ is due to its slower rate of homodehydrocoupling. With a CpCp*$TiMe_2$ catalyst the rate of dehydrocoupling of $PhSiH_3$ is relatively much slower than hydrosilation as compared to the Cp_2TiMe_2 catalyst, and successful hydrosilation can be achieved with this combination of reactants.

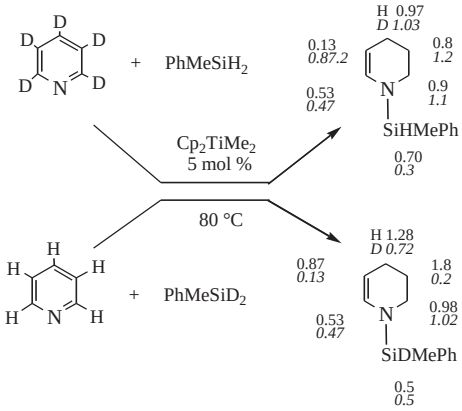
A reaction of CpCp*$TiMe_2$ with pyridine and $PhSiH_3$ (molar ratio of 1:2:4, respectively) at room temperature for four days gave 85% conversion of the pyridine to a mixture of *N*-(phenylsilyl)-1,2,3,4-tetrahydropyridine and *N*-(phenylmethylsilyl)-1,2,3,4-tetrahydropyridine. NMR spectroscopy showed the product also contained CH_4, $PhMeSiH_2$, and $PhMe_2SiH$, the usual products arising from methyl transfer reactions from the catalyst precursor (1*b*). The two *N*-silyl-tetrahydropyridine derivatives were present in a ratio of 4:1 and were the only observable pyridine-derived products. No CpCp*Ti species were detectable by NMR spectroscopy in the product. A similar reaction using $PhMeSiH_2$ instead of $PhSiH_3$ proceeded much more slowly to give the *N*-phenylmethylsilyl- and *N*-phenyldimethylsilyl-tetrahydropyridine products.

Influence of ring substitution on the rate of hydrosilation

The rates of reaction of some of the hydrosilations described above were qualitatively measured from the initial slopes of reactant concentration vs. time plots. The qualitative rate order from the reactants studied is shown in Scheme 1.

This sequence shows that the rate of ring hydrosilation correlates inversely with the basicity of the pyridine. Although no complexity constant data are available for this particular system, the first formation constant with alkyl pyridines for the later transition-metal consistently correlates with the basicity of the pyridine (22). There is no reason to believe that the case would be otherwise with the titanocene(III) system, and it is reasonable to infer that the

Fig. 2. Results of H–D exchange experiments with pyridine.



rate is higher the more weakly bound the pyridine is to the Ti center for the examples studied.

Experiments involving H–D exchange

^{1}H NMR spectra of reactions of pyridine-d_5 with $PhMeSiH_2$, and of unlabeled pyridine with $PhMeSiD_2$ in the presence of Cp_2TiMe_2, revealed extensive H–D exchange between unreacted pyridine and unreacted silane. The amount of exchange at the 2- and 6-positions of the recovered pyridine was much greater than at the other positions.

After hydrosilation–hydrogenation in these reactions had gone to completion, the recovered *N*-silyltetrahydropyridines showed minor, irregular H–D exchange at all positions of the reduced pyridine ring, with the 6-position clearly showing a higher extent of exchange than the others. The data for the two complementary exchange experiments are summarized in Fig. 2. It should be noted that the estimated errors in these NMR-determined values are about ±10%. Given the obvious complexity of the reactions leading to these products, and the likelihood of kinetic isotope effects, no real significance can be attributed to the small amounts of scrambling observed.

A reaction of Cp_2TiMe_2, pyridine-d_5, and $PhMeSiD_2$ gave *N*-(phenylmethyldeuterosilyl)-2,3,4-tetradeuteropyridine-d_5. Neither unreacted $PhMeSiD_2$, nor the small amount of $PhMe_2SiD$ produced by Me transfer from Cp_2TiMe_2 to silicon, showed any evidence of H incorporation into the Ph or Me groups. There was also no NMR evidence for migration of D to the Cp rings nor for transfer of D to, or from, toluene solvent.

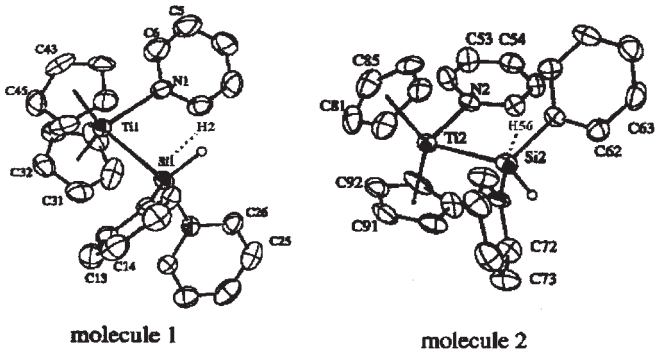
Reactions of pyridine with H_2

Given the activity of the titanocene system for the hydrosilation of the pyridine ring, its activity for hydrogenation was also studied. A preprepared $[Cp_2TiH]_2$ catalyst (20) proved to be weakly active for hydrogenation of pyridine (~5% conversion to piperidine after 24 h at 80°C under 400 psi H_2, 1 psi = 6.894 kPa). However, under these conditions, pyridine-d_5 underwent essentially complete exchange of H with the D at the 2- and 6-positions of the unreacted pyridine.

Titanocene(III) (silyl)pyridine and pyridyl complexes

Complexes of the general type $Cp_2Ti(SiHRR')(py)$ (**9**) (R = H, alkyl, or aryl; R′ = alkyl or aryl; py = pyridine or substituted pyridine) can be easily prepared by precipitation from mixtures of the appropriate pyridine and $[Cp_2Ti(SiHRR')]_2$ in toluene (1*b*). The same compound precipitates in a one-pot reaction of Cp_2TiMe_2, $RR'SiH_2$, and the appropriate pyridine in toluene (19). The products are generally purple, air-sensitive, microcrystalline solids with low solubility in hydrocarbon solvents.

Fig. 3. The two conformers of **9a** in the solid state. The ORTEP thermal ellipsoids are shown at the 30% probability level (19).



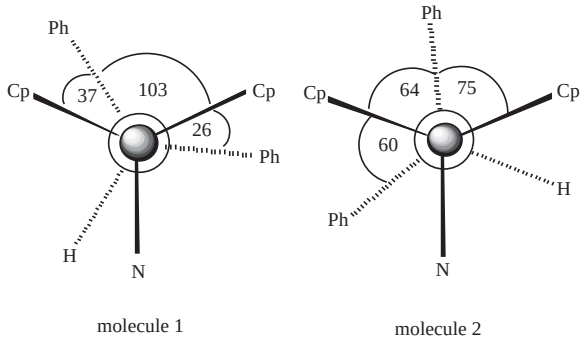
Crystals suitable for structure determination by X-ray diffraction analysis were obtained for the case py = pyridine and R = R′ = Ph, **9a**. The monoclinic crystals contain eight formula units of **9a** and two disordered molecules of pyridine solvent in the unit cell. The eight molecules of **9a** are present as two conformers, molecule 1 and molecule 2, as shown in Fig. 3 (19).

The structure of **9a** can be compared to the analogous Me_3P complex (23). The Ti—Si bond lengths of the two conformers of **9a** are within the range observed for $Cp_2Ti(SiR_3)(PMe_3)$ complexes. However, the Si-Ti-N bond angles of the two conformers of **9a** are quite different from each other and significantly larger (87.2(2)° for molecule 1 and 91.4(2)° for molecule 2) than those in the Me_3P complexes with $SiHPh_2$ (84.8(1)°), SiH_2Ph, and SiHPhMe (both 80.9(1)°) ligands (23). The fact that the angles between the Si-Ti-N planes and the pyridine ring planes of the two conformers are quite different (28.8(4)° for molecule 1 and 14.8(3)° for molecule 2) suggests that steric effects are largely responsible for these differences.

Molecule 2 is close to a gauche configuration (Fig. 4) and, hence, intramolecular contacts are minimized. On the other hand, molecule 1 is constrained, presumably by lattice forces, to a conformation that is much closer to eclipsed. In both conformers there is a close contact between Si and the *ortho*-hydrogen, H(2) (2.83 Å, molecule 1), or H(56) (2.82 Å, molecule 2), which is responsible for the tilting of the pyridine ring. These calculated distances are much shorter than the calculated contact radius sum (3.3 Å) and probably represent a minimum approach that can be tolerated without some distortion of the molecule. In molecule 1, the smaller Si(1)-Ti(1)-N(1) angle increases the encroachment of the Si on H(2), forcing a larger tilting of the pyridine ring plane. There are also important changes in the orientations of the phenyl groups to accommodate the differing steric interactions in the two conformers.

Compounds **9** with R and (or) R′ = alkyl are more soluble, and more prone to decomposition, than those where R and R′ = Ph or H. Thus, reactions of $PhMeSiH_2$, or *n*-$BuMeSiH_2$,

Fig. 4. Projections of molecules 1 and 2 along the Ti–Si bond.



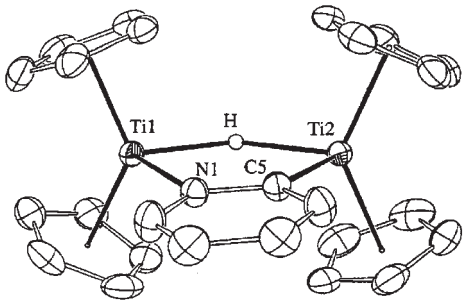
with Cp_2TiMe_2 in the presence of pyridine initially give purple solutions of **9**, but these solutions rapidly darken at room temperature and eventually precipitate dark brown crystals of a new compound, **10**.

The structure of **10** (Fig. 5) closely resembles those of several other hydride-bridged bimetallic titanocene complexes whose structures have been reported. $Cp_2Ti(\mu\text{-}H)(\mu\text{-}HSiHPh)TiCp_2$ (**11**) (1*b*), $Cp_2Ti(\mu\text{-}H)(\mu\text{-}PCy_2)TiCp_2$ (**12**) (24), and $CpTi(\mu\text{-}H)(\mu\text{-}\eta^5,\eta^5\text{-}C_{10}H_8)(\mu\text{-}Cl_2AlEt_2)TiCp$ (25) all have the motif of two titanocene-derived units connected by one hydride bridge and one formally uninegative ligand bridging through a lone pair. The Ti—H bond distances in **10** (1.92(2) and 1.91(2) Å) are not significantly different from those of **11** (1.97(4) Å) and **12** (2.01(5) and 2.00(5) Å). Similarly, the Cp—Ti distances (2.09(1) Å) and Cp-Ti-Cp angles (131.8(2) and 132.7(3)°) in **10** are also close to the corresponding values in **11** (2.053(3) to 2.081(4) Å; 130.6(1) and 131.1(1)°) (R = H, R′ = Ph) and **12**. The Ti(1)—C(5) length (2.205(2) Å) is the same as the Ti(2)—N length, as a result of the C–N disorder. This length is close to the lengths (2.18 to 2.19 Å) found for other sp^2-C ligands bound to titanocene (26), and the same as the Ti—N distance (2.202(2) Å) in a dimeric titanocene(III) pyrazole complex (2.206(4) Å) (27). It is slightly longer than the Ti—N length in titanocene(II)bipyridyl (2.14(2) Å) (28). In the similar monometallic species $Cp^*_2Sc(\eta^2\text{-}N,C\text{-}C_5H_4N)$ (29) and $[Cp_2Zr(\eta^2\text{-}N,C\text{-picolyl})(PMe_3)]^+$ (30) the M—C bonds are slighly longer than the M—N bonds.

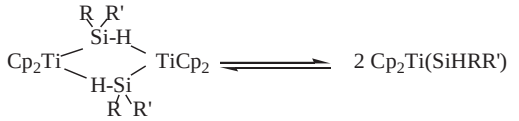
The mechanism of the formation of 9 and 10

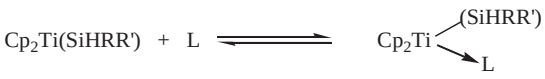
The Cp_2TiMe_2 catalyzed silane dehydrocoupling reaction of $PhMeSiH_2$ is almost completely suppressed in the presence of pyridine, 3- and 4-methylpyridine, or 3,5-lutidine. 2,6-Lutidine has no influence on the dehydrocoupling reaction, behaving essentially as an inert solvent. In the latter case, no complex **9** could be detected (by EPR spectroscopy), or isolated. It is, therefore, likely that the formation of **9** blocks the activity of those titanocene species responsible for the dehydrocoupling reaction. These results provide strong evidence in support of the equilibria shown in eqs. [7] and [8]. In the absence of a donor ligand L, the equilibrium in eq. [7] shifts to the left to give the Si-H bridged bimetallic complex (23a). In the presence of a strong donor ligand, such as a pyridine, or trimethylphosphine, the equilibrium in eq. [8] shifts to the right to produce the ligated, monometallic titanocene(III) silyl complexes. The influence

Fig. 5. The structure of **10**. The ORTEP thermal ellipsoids are shown at the 30% probability level (19)

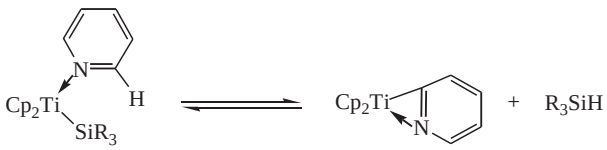


of the steric bulk of both the silyl and the donor ligands on the equilibria is very evident. As mentioned above, with bulkier donor ligands, such as 2,6-dimethylpyridine or triphenylphosphine, formation of the ligated silyl complex is inhibited and the equilibria shift towards the left. Bulkier silyl groups can also prevent the formation of a ligated complex.

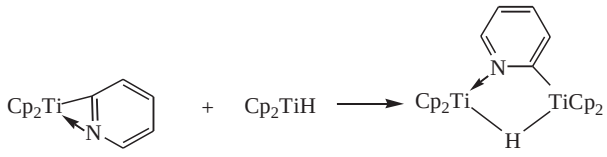
[7] 

[8] 

The formation of **10** could take place through a number of plausible routes. One would be the prior formation of $Cp_2Ti(\eta^2\text{-}N,C\text{-pyridyl})$ (**13**) by the 1,3-silane elimination reaction shown in eq. [9], followed by reaction with Cp_2TiH (eq. [10]). Reaction [9] is strongly favored by the close approach of the Si to the proximal pyridine C-H hydrogen, revealed in the structure of **10**. In such a mechanism, the activation energy would be relatively low, since the Ti could move from $\eta^1\text{-}N$ coordination to $\eta^2\text{-}N,C$ coordination with relatively little sacrifice in energy. A similar process was previously proposed by Klei and Teuben (30) for the decomposition of $Cp_2Ti(alkyl)(py)$ complexes, and this type of coordination has been demonstrated for a number of metals (31, 32). However, **13** has not been thoroughly structurally characterized. *ortho*-Metallations of pyridine by other early transition metals have also been reported (33–35). The reaction mechanism seems to be similar in all of these systems.

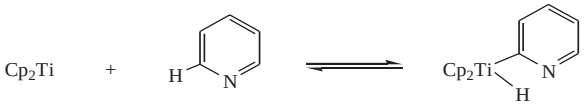
[9] 

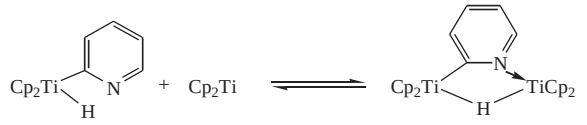
13

[10] 

Another mechanism analogous to eq. [9], but involving Cp_2TiH(pyridine) (**14**), rather than $Cp_2Ti(SiR_3)$(pyridine), is also plausible. Attempts to detect **14** during hydrosilation reactions, or during the synthesis of **10**, were unsuccessful. This is not surprising since **14**, generated at –20°C by reaction of $[Cp_2TiH]_2$ (21) with pyridine, decomposes rapidly on warming to room temperature. The product of this decomposition exhibits an EPR signal (g = 1.9905), which is very close to that reported for the putative $Cp_2Ti(\eta^2$-*N*,*C*-$MeC_5H_3N)$ (30). It is possible that both of these intramolecular eliminations participate in the production of **10**. Although there is little doubt that the hydride route occurs rapidly in the absence of any silyl ligands, the same cannot be said for the silyl route, since primary and secondary titanocene silyls are known to decompose to produce titanocene hydrides.

A third plausible mechanism for the production of **10** is reaction of a molecule of a Cp_2TiH(pyridyl) complex (**14**) with Cp_2Ti. The former complex could be produced by a concerted oxidative addition of a pyridine C-H bond to Cp_2Ti, as shown in eqs. [11] and [12]. A similar process was proposed earlier to explain the formation of **11** (1*b*). We have also previously suggested that Cp_2Ti could be produced as a transient intermediate in the reactions of Cp_2TiMe_2 with silanes. It is possible that the pyridine competes more effectively for the titanocene intermediate than the less reactive secondary silanes, resulting in the formation of a hydrido(pyridyl), rather than a silyl(pyridine) product. The more reactive silanes (phenylsilane and diphenylsilane) could compete more effectively than the pyridine for titanocene.

[11] 

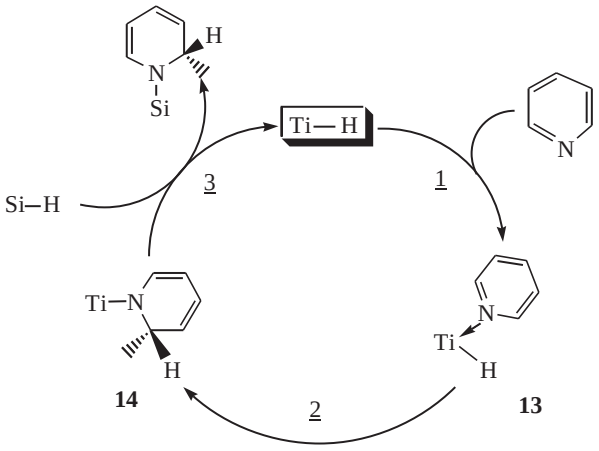
[12] 

The mechanism of the hydrosilation–hydrogenation of pyridines

The results described above indicate that the reactions proceed first by hydrosilation, followed by hydrogenation. The diene resulting from the initial hydrosilation step is expected to be a good substrate for titanocene-catalyzed hydrogenation by the by-product H_2 from dehydrocoupling reactions, or by direct titanium-mediated transfer of H from Si-H, since such cohydrogenation is commonly used in titanocene catalyzed dehydrocoupling reactions (10, 36).

The isolation of complexes **9** supports the assumption that Cp_2Ti^{III}(silyl)(py) complexes are intermediates, or at least catalytic precursors, in the hydrosilation–hydrogenation reactions. On the other hand, the deuterium–proton exchanges between substrates, or between substrates and H_2, clearly indicate the participation of undetected hydride species as well. Isotope exchange between Si-H and the 2- and 6-positions of pyridine substrates can be accounted for by assuming that eq. [9] is reversible. There are a number of other

Fig. 6. A Ti-H based catalytic cycle.



examples of such *ortho*-metallations of pyridine, involving Ti^{III} and other transition metal ions (27, 34, 35). Exchanges at other positions of the ring are expected to occur by conventional reversible β-hydride addition–elimination cycles as further hydrogenation of the *N*-silyldihydropyridine proceeds. However, the results summarized in Fig. 2 show there is relatively little H–D scrambling in the product other than at the 6-position.

The hydrosilation of pyridines is a special case of imine hydrosilation. Willoughby and Buchwald (9) proposed a plausible mechanism for ketimine hydrosilation involving a classical hydrometallation. The pyridine analogue of this mechanism is illustrated in Fig. 6. In this figure the catalytic cycle is carried by a Ti-H species and silylation occurs by a σ-bond metathesis between Si-H and Ti-N.

Since very little direct hydrogenation of pyridine occurs with these catalysts, it is unlikely that the initial step involves addition of a Ti-H bond to the C=N bond of pyridine. An alternative mechanism involves a cycle in which it is Ti-Si that carries the catalysis, as shown in Fig. 7. This is supported to some degree by the regioselectivities observed with 3-picoline as the substrate. If there is a methyl group at the 3-position of the pyridine, steric hindrance will induce the bulky Cp_2Ti group to move to the 6-position rather than the 2-position, as illustrated in Fig. 8. This is indeed the regioselectivity observed in the lower temperature regime (see Table 1). At higher temperatures, the relative rate of the higher activation energy process of migration of the Cp_2Ti towards the 2-position will increase, as observed. In the case of the Ti-H mechanism, there would be little steric preference for the migration of H to the 2- or the 6-position.

There is ample evidence for both M–H addition and M–Si addition occurring in later transition metal catalyzed olefin hydrosilation (37). M–H addition will normally be faster than M–Si addition. However, β-hydrogen elimination can also be so fast, particularly in the present case where it involves rearomatization, that formation of product is frustrated. In such a situation, the slower M–Si addition can lead to product if the reverse process is also relatively slow.

The minor amounts of H–D scrambling observed in the isotopic labeling experiments show that the hydrogen transfer steps following hydrosilation are essentially irreversible. The larger amount of scrambling at the 6-position in these

Fig. 7. A Ti-Si based catalytic cycle.

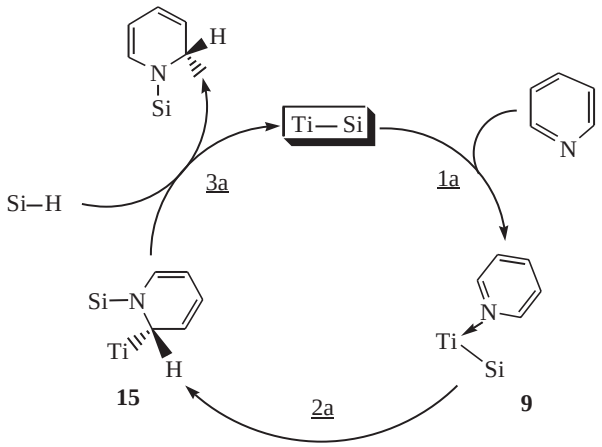
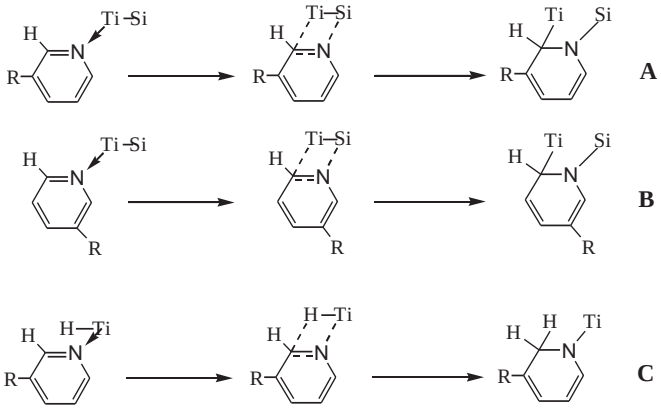


Fig. 8. The two alternative reaction coordinates for C=N insertion into the Ti–Si bond. At 25°C **a**:**b** > 15; at 50°C **a**:**b** = 3.



experiments cannot be attributed to an *ortho*-metalation, such as eq. [9], since this would also cause a similar amount of scrambling at the 2-position. The apparent absence of scrambling at the 2-position requires that the rate of the initial addition of Si-H to N=C be faster than the process that leads to isotope exchange at the 2- and 6-positions of the *unreacted* pyridine. Also, the enhanced exchange at the 6-position of the hydrosilated–hydrogenated product most likely results from an unproductive β-hydride addition–elimination reaction of the eneamine, due to stabilization of the double bond through conjugation to the N.

Once the hydrosilation step has occurred, the nature of the final observed products is determined by the outcome of a complicated set of reactions, including double bond migrations and hydrogenations, effected by reversible β-hydride addition–elimination reactions. The degree to which the products from the alkyl-substituted pyridines are kinetically, or thermodynamically, determined is the subject of continuing study.

The resistance of the enamine products to complete saturation could be due to the stabilization of one of the critical intermediates in the hydrogenation cycle by intramolecular *N*-coordination, or simply because of the unusual stability of the double bond through conjugation to the N lone pair. Blocking of the reaction at the diene level in the case of 3,5-lutidine appears to be the consequence of the much lower reactivity of a trisubstituted double bond towards hydrogenation in this system. In the case of the 3-picoline reaction, a similar lowering of reactivity explains the resistance of **2** to hydrogenation.

The influence of ring substitution on rate.

The reactivity order for the series of substituted pyridines shown above correlates with the basicity of the pyridine. Since the stability of complexes **9** should increase with the basicity of the pyridine, we conclude that tight binding of the pyridine to the Ti has a negative effect on reaction rates, presumable by increasing the activation energy of step 2*a* in Fig. 7. If binding becomes too weak, as in the case of substrates with substituents at the 2- or 6-positions, then reaction is also inhibited.

The dramatic reversal of chemical selectivity between ethyl nicotinate and ethyl isonicotinate may also be due to the fact that the ester group in the 4-position lowers the binding of the N to Ti, relative to binding of the ester function, to the point that ester reduction is the dominant reaction. With the ester group in the 3-position the absence of conjugation between the ester and N leaves the N sufficiently basic, which is the preferred coordination site.

Conclusions

Titanocene derivatives show an exceptional activity for the catalytic hydrosilation of pyridines and, to date, are the only known homogeneous catalysts for this reaction. The reactions show interesting variations in the level of reduction and regioselectivity of the substrate, depending on the ring substitution and the reaction conditions. The ability of the catalyst to effect hydrogenation in the presence of H_2 allows the synthesis of dihydro- and tetrahydro-pyridines, and piperidines in reasonable yields using a single catalyst system. An unusual chemical selectivity is observed with nicotinic and isonicotinic esters. In the former case, only reduction of the ring occurs, while in the latter exclusive reduction of the ester is observed. These results illustrate the extreme sensitivity of the reactions to electronic and steric effects.

The initial step in the reaction appears to be the addition of a Ti–Si species across the C=N bond of the pyridine to give an *N*-silyldihydropyridine. A further two hydrogen atoms can be transferred to give the tetrahydropyridine, but complete reduction only occurs in the presence of H_2.

We are continuing to study the reactions of prochiral pyridines in the presence of chiral titanocene catalysts.

Experimental

All manipulations were performed under an atmosphere of argon, using standard Schlenk techniques. Dry, oxygen-free solvents were employed throughout. Glassware was flame-dried, or oven-dried, before use.

Elemental analyses were performed by Galbraith Laboratories, Inc., and by Oneida Research Services, Whitesboro, New York. $LiAlD_4$, $LiAlH_4$, *n*-BuLi, and Cp_2TiCl_2 (Aldrich) were used as received. Pyridine-d_5 (Aldrich) was dried over

4 Å molecular sieves. Pyridine and alkyl pyridines (Aldrich) were distilled over calcium hydride before use. Quinoline (Aldrich) was distilled under reduced pressure before use. Organosilanes and deuterated organosilanes were prepared from the corresponding chlorosilanes (Hüls America) by reduction with $LiAlH_4$ ($LiAlD_4$) (38). Cp_2TiMe_2 (39) and $CpCp^*TiMe_2$ (40) were prepared according to literature procedures.

Manipulation of air-sensitive crystals was performed either in standard Schlenk apparatus, or in a Braun LabMaster 130 inert-atmosphere glove-box equipped with a catalytic purifier and an Ar atmosphere circulation system. Both H_2O and O_2 were maintained at <2 ppm.

^1H and ^{13}C NMR spectra were recorded on a Varian Unity 500 FT spectrometer operating at 499.9 MHz for ^1H and 125.7 MHz for ^{13}C. ^1H spectra were referenced to C_6H_5D in C_6D_6 (δ 7.15). ^{13}C NMR spectra were referenced to C_6D_6 (δ 128.0). Silicon NMR spectra were recorded in C_6D_6 on a Varian XL-300 spectrometer operating at 59.9 MHz and employing a DEPT pulse sequence (41). The structures of all organic products were confirmed using COSY and HQMC methods. An external standard of tetramethylsilane was used.

Mass spectra were recorded on a KRATOS MS25RFA spectrometer equipped with a KRATOS DS90 data system.

Preparation of $Cp_2Ti(SiHPh_2)(py)$ (9a)

This complex was prepared using a modification of the method for the preparation of titanocene(silyl)trimethylphosphine complexes (22). Typically, Cp_2TiMe_2 (75 mg, 0.36 mmol) was added to a solution of diphenylsilane (0.17 mL, 0.72 mmol) and pyridine (0.5 mL, 6.20 mmol.) in *n*-hexane–toluene (6 mL, 5:1 v/v). In the course of 4 h, the solution turned dark brown and then deep violet. After a further 16 h at room temperature, the solution was stored at –20°C for 2 days to yield small, dark violet needles of **9** (yield: 146 mg, 92%). Anal. calcd. for $C_{28.25}H_{27.25}N_{1.25}SiTi$: C 73.72, H 5.97, N 3.81, Si 6.10, Ti 10.40; found: C 72.83, H 5.99, N 3.22, Si 5.98, Ti 10.26. The instability of this compound in solution precluded recrystalization and X-ray data were obtained on crystals isolated directly from the reaction. The X-ray structure showed the presence of 0.25 molecules of lattice pyridine per molecule of **9** (19).

Preparation of $Cp_2Ti(\mu\text{-}H)(1\kappa N,2\kappa C\text{-pyridyl})TiCp_2$ (10)

Cp_2TiMe_2 (120 mg, 0.58 mmol) was added to a solution of phenylmethylsilane (0.24 mL, 1.73 mmol) and pyridine (1.0 mL, 12.4 mmol) in *n*-hexane–toluene (6:1 v/v, 7.0 mL). After standing for 2 h without stirring, the solution had turned deep violet in color. On standing for a further 24 h at room temperature, the solution slowly turned dark brown. It was then kept at 5°C for 1 day to yield dark brown plates suitable for X-ray analysis (yield: 83 mg, 56%). Anal. calcd. for $C_{27.5}H_{27.5}N_{1.5}Ti_2$: C 69.56, H 5.84, N 4.42, Ti 20.18; anal. calcd. for $C_{26}H_{26}Ti_2N$: C 68.98, H 5.79, N 3.22, Ti 22.01; found: C 66.27, H 5.12, N 3.04, Ti 22.33. The X-ray structure of these crystals showed the presence of 0.5 molecules of lattice pyridine per molecule of **10** (19). The poor elemental analysis resulted in part from loss of lattice pyridine from the crystal during vacuum drying of the sample. EPR: (toluene, 220 K): g_{iso} = 1.984, A_{Ti} = 12 G.

The ^1H NMR spectrum of a saturated solution of **10** in toluene-d_8 at room temperature consisted of two very broad, unresolved, paramagnetically shifted peaks at δ 31.6 (20H, Cp) and 15.6 (4H, pyridyl). No resonance assignable to the bridging hydride was detected.

Catalytic hydrosilation–hydrogenation reactions of pyridines

Synthesis of N-*(phenylmethylsilyl)-2,3,4-tetrahydropyridine*

$PhMeSiH_2$ (3.5 mL, 25.6 mmol) and pyridine (1.0 mL, 12.5 mmol) were added to Cp_2TiMe_2 (0.13 g, 0.7 mmol, 6 mol% catalyst based on pyridine). After a while, the solution color changed to dark blue, then purple accompanied by gas evolution. The mixture was stirred at 80°C. After 12 h an ^1H NMR spectrum of the dark-brown-purple reaction mixture showed that >95% of the pyridine had reacted to give a yield of ca. 80% of *N*-(phenylmethylsilyl)-2,3,4-tetrahydropyridine. The crude product was distilled under vacuum to give 1.29 g (50% isolated yield) *N*-(phenylmethylsilyl)-2,3,4-tetrahydropyridine as a colorless liquid (bp 57°C, 0.12 mm Hg). EI-MS *m/z* (%): 203 (M^+, 100), 188 ([M – $CH_3]^+$ 18.5), 121 ([M – $C_5H_8N]^+$, 76.6). ^1H NMR (300 MHz, benzene-d_6, 22°C) δ: 0.28 (d, *J* = 3.3 Hz, 3H, $SiCH_3$), 1.57 (m, 2H, $NCH_2CH_2CH_2CH$=CH), 2.00 (m, 2H, $NCH_2CH_2CH_2CH$=CH), 2.99 (m, 2H, $NCH_2CH_2CH_2CH$=CH), 4.62 (m, 1H, $NCH_2CH_2CH_2CH$=CH), 5.01 (q, *J* = 3.3 Hz, 1H, SiH), 6.28 (dt, ^3J = 7.8 Hz, ^4J = 3.0 Hz, 1H, $NCH_2CH_2CH_2CH$=CH), 7.2 and 7.5 (2m, 5H, C_6H_5). $^{29}Si\{^1H\}$ NMR (59.9 MHz, benzene-d_6, 22°C) δ: –9.1.

Synthesis of N-*(phenylmethylsilyl)piperidine*

$PhMeSiH_2$ (5.0 mL, 36.5 mmol), pyridine (2.0 mL, 24.7 mmol), and Cp_2TiMe_2 (0.36 g, 1.72 mmol) were thoroughly mixed and sealed in a glass lined, stirred autoclave. The conditions were set at 80°C and 250 psi H_2. After 24 h, *N*-(phenylmethylsilyl)-piperidine (2.0 g, 40% based on pyridine) was isolated by vacuum distillation as a pale yellow liquid (bp 54–56°C, 0.01 mm Hg).^1H NMR (500 MHz, benzene-d_6, 22°C) δ: 0.29 (d, *J* = 3.0 Hz, 3H, $SiCH_3$), 1.27 (m, 4H, $NCH_2CH_2CH_2CH_2CH_2$), 1.40 (q, *J* = 5.5 Hz, 2H, $NCH_2CH_2CH_2CH_2CH_2$), 2.8 (m, 4H, NCH_2CH_2 $CH_2CH_2CH_2$), 5.02 (quart, *J* = 3.0Hz, 1H, SiH), 7.22 and 7.58 (2m, 5H, C_6H_5). $^{29}Si\{^1H\}$ NMR (59.9 MHz, benzene-d_6, 22°C) δ: –10.5. COSY and HMQC NMR experiments were in conformity with the structure assignment.

Reactions of C_5H_5N with $PhMeSiD_2$ and C_5D_5N with $PhMeSiH_2$

$PhMeSiD_2$ (0.44 mL, 3.2 mmol) and pyridine (0.09 mL, 1.0 mmol) were added to Cp_2TiMe_2 (23 mg, 0.11 mmol, 10 mol% catalyst per pyridine). After a while, the solution color changed from orange to dark blue, then to purple accompanied by gas evolution. The mixture was stirred at 80°C. After 12 h an ^1H NMR spectrum indicated that *N*-(phenylmethylsilyl)-2,3,4-tetrahydropyridine(H/D) had been produced in 94% yield, based on pyridine. After exposure to dry air to oxidize the catalyst, the ^1H and ^2H NMR spectra were recorded without further purification.

A reaction between $PhMeSiH_2$ (0.89 mL, 6.5 mmol) and pyridine-d_5 (0.35 mL, 4.32 mmol) was carried out in the

presence of Cp_2TiMe_2 (45 mg, 0.22 mmol, 5 mol%). The mixture was stirred at 80°C for 8 h and then distilled under vacuum to give 0.19 g (20% isolated yield, bp 57°C, 0.12 mm Hg) of *N*-(phenylmethylsilyl)-2,3,4-tetrahydropyridine(H/D) as a colorless liquid

Reaction of Cp_2TiMe_2, pyridine-d_5, and $PhMeSiD_2$ under H_2

$PhMeSiD_2$ (0.30 mL, 2.2 mmol), and pyridine-d_5 (0.12 mL, 1.4 mmol) were added to Cp_2TiMe_2 (0.15 g, 0.36 mmol). The reaction mixture was stirred at room temperature under H_2 (1 atm). After three days, the dark-brown solution was fractionally distilled to give 0.18 g of *N*-(phenylmethylsilyl)-2,3,4-tetrahydropyridine(H/D) as a colorless liquid.

Reaction of 3-picoline, Cp_2TiMe_2, and $PhMeSiH_2$

$PhMeSiH_2$ (3.56 mL, 26 mmol), 3-picoline (1.8 mL, 18.4 mmol), and Cp_2TiMe_2 (0.40 g, 1.8 mmol) were added to a Schlenk tube and stirred at 80°C. After six days, the dark brown–purple reaction mixture was distilled under vacuum (yield 1.3 g, bp 84–86°C, 0.02 mm Hg). NMR showed the product to be a mixture of **1** and **2** (in a ratio of 3:2, respectively). **1**: ^{1}H NMR (500 MHz, benzene-d_6, 22°C) δ: 0.72 (m, 3H, $NCH_2C(H)(CH_3)CH_2CH{=}CH$), 1.64 (m, 1H, $NCH_2C(H)(CH_3)CH_2CH{=}CH$), 2.04, 1.71 (m, 2H, $NCH_2C(H)(CH_3)CH_2CH{=}CH$), 2.98, 2.60 (m, 2H, $NCH_2C(H)(CH_3)CH_2CH{=}CH$), 4.57 (m, 1H, $NCH_2C(H)(CH_3)CH_2CH{=}CH$), 4.99 (quart, J = 3.5 Hz, 1H, SiH), 6.22 (t, J = 8.5 Hz, 1H, $NCH_2C(H)(CH_3)CH_2CH{=}CH$), 7.2, 7.5 (m,$C_6H_5$). EI-MS *m*/*z* (%): 217 ([M^+], 100), 202 ([M – $C_7H_9Si]^+$, 50), 121 ([M – $C_9H_{10}N]^+$, 26). **2**: ^{1}H NMR (500 MHz, benzene-d_6, 22°C) δ: 0.28 (d, J = 3.4 Hz, 3H, $SiCH_3$), 1.54 (m, 2H, $NCH{=}C(CH_3)CH_2CH_2CH_2$), 1.61 (d, J = 1.0 Hz, 3H, $NCH{=}C(CH_3)CH_2CH_2CH_2$), 1.85 (t, J = 6.25 Hz, 2H, $NCH{=}C(CH_3)CH_2CH_2CH_2$), 2.91 (m, 2H, $NCH{=}C(CH_3)CH_2CH_2CH_2$), 5.02 (quart, J = 3.4 Hz, 1H, SiH), 6.08 (m, 1H, $NCH{=}C(CH_3)CH_2CH_2CH_2$), 7.2 and 7.5 (2m, 5H, C_6H_5).

Reaction of 3-picoline, Cp_2TiMe_2, and $PhMeSiH_2$ under H_2

$PhMeSiH_2$ (3.56 mL, 26 mmol), 3-picoline (1.8 mL, 18.4 mmol), and Cp_2TiMe_2 (0.40 g, 1.8 mmol, 10 mol%) were added to a 50 mL stirred pressure bomb and heated at 80°C under hydrogen (200 psi). After four days the product was shown by ^{1}H NMR to be mainly a mixture of **2** and **4**, in a ratio of 3:7. The mixture was fractionally distilled under vacuum to give 1.0 g of pure **2** (bp 84–86°C, 0.02 mm Hg).

Synthesis of N*-(phenylmethylsilyl)-2,3,4-tetrahydro-4-picoline*

A mixture of $PhMeSiH_2$ (3.56 mL, 26 mmol), 4-picoline (1.8 mL, 18.4 mmol), and Cp_2TiMe_2 (0.40 g, 1.8 mmol) was stirred at 80°C for six days and then distilled under vacuum to give *N*-(phenylmethylsilyl)-2,3,4-tetrahydro-4-picoline as a colorless liquid (2.1 g, 53% isolated yield based on 4-picoline, bp 85–87°C, 0.15 mm Hg). EI-MS *m*/*z* (%): 217 (M^+, 37), 202 ([M – $CH_3]^+$, 100), 121 ([M – $C_5H_8N]^+$, 37). ^{1}H NMR (200 MHz, benzene-d_6, 22°C) δ: 0.30 (d, J = 3.3 Hz, 3H, $SiCH_3$), 1.0 (d, J = 6.8 Hz, 3H, $NCH_2CH_2CH(CH_3)CH{=}CH$), 1.6, 1.3 (m, 2H, $NCH_2CH_2CH(CH_3)CH{=}CH$), 2.28 (m, 1H, $NCH_2CH_2CH(CH_3)CH{=}CH$), 3.02 (m, 2H, $NCH_2CH_2CH(CH_3)CH{=}CH$), 4.56 (dd, ^3J = 7.8 Hz, $^3J'$ = 3.0 Hz, 1H $NCH_2CH_2CH(CH_3)CH{=}CH$), 5.04 (quartet, J = 3.3 Hz, 1H, SiH), 6.26 (dd, ^3J = 7.8 Hz, ^4J = 1.8 Hz, 1H, $NCH_2\ CH_2CH(CH_3)CH{=}CH$), 7.2 and 7.5 (2m, 5H, C_6H_5).

Preparation of N*-(phenylmethylsilyl)-2,3,4-tetrahydroquinoline*

$PhMeSiH_2$ (6.0 mL, 43.2 mmol) and quinoline (3.3 mL, 28.8 mmol) were added to Cp_2TiMe_2 (0.60 g, 2.88 mmol, 10 mol%) in a stirred autoclave under 200 psi of H_2 at 80°C. After 48 h, *N*-(phenylmethylsilyl)-2,3,4-tetrahydroquinoline was vacuum distilled as a yellowish liquid (4.0g, 54% isolated yield, bp 160°C, 0.02 mm Hg). EI-MS *m*/*z* (%): 253 ([M^+], 100), 132 ([M – $C_7H_9Si]^+$, 38.3), 121 ([M – $C_9H_{10}N]^+$, 42.1). ^{1}H NMR (200 MHz, benzene-d_6, 22°C) δ: 0.44 (d, J = 3.4 Hz, 3H, $SiCH_3$), 1.55 (m, 2H, $NCH_2CH_2CH_2$), 2.60 (t, J = 6.6 Hz, 2H, $NCH_2CH_2CH_2$), 3.11 (m, 2H, $NCH_2CH_2CH_2$), 5.37 (quart, J = 3.4 Hz, 1H, SiH), 6.7–7.2 and 7.5–7.7 (2m, 4H, CH on the phenylene ring). ^{29}Si NMR (59.9 MHz, benzene-d_6) δ: –12.6 ppm.

Reaction of quinoline, Cp_2TiMe_2, and $PhMeSiH_2$

$PhMeSiH_2$ (2.0 mL, 14.4 mmol) and quinoline (1.1 mL, 9.6 mmol) were added to Cp_2TiMe_2 (0.20 g, 0.96 mmol, 10 mol%) and stirred at 80°C for 36 h. *N*-(Phenylmethyl-silyl)-2,3,4-tetrahydroquinoline and *N*-(phenylmethylsilyl)-2-dihydro-quinoline were formed in a ratio of 3:1, respectively. ^{1}H NMR *(N*-(phenylmethylsilyl)-2-dihydro-quinoline) (200 MHz, benzene-d_6, 22°C) δ: 0.38 (d, J = 3.3 Hz, 3H $SiCH_3$), 3.48 (m, 2H, $NCH_2CH{=}CH$), 4.71 (m, 1H, $NCH_2CH{=}CH$), 6.22 (d, ^2J = 7.7 Hz, 1H, $NCH_2CH{=}CH$). ^{29}Si NMR (59.9 MHz, benzene-d_6): –10.6. A small amount of 1,2,3,4-tetrahydroquinoline was also detected in the mixture: ^{1}H NMR (500 MHz, benzene-d_6, 22°C) δ: 1.57 (m, 2H, $NCH_2CH_2\ CH_2$), 2.51 (t, J = 6.3 Hz, 2H, $NCH_2CH_2CH_2$), 2.76 (t, J = 5.54 Hz, 2H, NCH_2), 3.0 (br s, 1H, NH), 6.22 (d, J = 8.0 Hz, 1H), 6.62 (t, J = 7.0 Hz, 1H), 6.85 (d, J = 7.0 Hz, 1H), 6.95 (t, J = 7.0 Hz, 1H).

Reaction of 3,5-lutidine and $PhMeSiH_2$

$PhMeSiH_2$ (3.56 mL, 26 mmol), 3,5-lutidine (2.1 mL, 18.4 mmol), and Cp_2TiMe_2 (0.31 g, 1.41 mmo, 8 mol%) were mixed a Schlenk tube. After a while the solution turned dark blue, then violet, progressively accompanied by gas evolution. The violet solution was stirred at 80°C for 8 days, and then distilled under vacuum. Analysis of the crude product by ^{1}H NMR showed a complete conversion of the lutidine and a 70% yield of *N*-(phenylmethylsilyl)-4-dihydro-3,5-lutidine. Fractional distillation yielded the pure dihydropyridine (2.5 g, 60% yield, bp 80–90°C, 0.02 mm Hg). FAB-MS (NBA) *m*/*z*: 229 [M^+]. ^{1}H NMR (500 MHz, benzene-d_6, 22°C) δ: 0.25 (d, J = 3.0 Hz, 6H $NCH{=}C(CH_3)CH_2C(CH_3){=}CH$), 2.69 (s, 2H, $NCH{=}C(CH_3)CH_2C(CH_3){=}CH$), 4.99 (quartet, J = 3.0 Hz, 1H, SiH), 5.87 (s, 2H, $NCH{=}C(CH_3)CH_2C(CH_3){=}CH$), 7.2 and 7.5 (2m, 5H, C_6H_5). ^{29}Si NMR (59.9 MHz, benzene-d_6, 22°C) δ: –8.0.

Reaction of ethyl nicotinate and $PhMeSiH_2$ in the presence of Cp_2TiMe_2

$PhMeSiH_2$ (0.45 mL, 3.3 mmol) and ethyl nicotinate (0.3 mL, 2.2 mmol) were added to Cp_2TiMe_2 (40 mg, 0.20 mmol). After a while, the solution color changed from orange to dark blue, then purple, accompanied by gas evolution. The mixture was stirred at 80°C for 3 h, at which point an ^1H NMR spectrum of the product showed that conversion of ethyl nicotinate was complete and ethyl *N*-(phenylmethylsilyl)-1,6-dihydronicotinate was produced in 90% yield. EI-MS *m*/*z* (%): 274 ($[M + 1]^+$, 3.6), 196 ($[M - C_6H_5]^+$, 4.4). ^1H NMR (200 MHz, benzene-d_6, 22°C) δ: 0.06 (d, J = 3.5 Hz, 3H, $SiCH_3$), 0.97 (t, J = 7.2 Hz, 3H, OCH_2CH_3), 3.32 (m, 2H, NCHC(OEt)CHCHCH_2), 4.06 (t, J = 7.2 Hz, 2H, OCH_2CH_3), 4.60 (dt, J = 8.0 Hz, J' = 3.4 Hz, 1H, NCH=C(OEt)CH=CHCH$_2$), 4.72 (q, J = 3.5 Hz, 1H, SiH), 5.58 (dm, J = 8.0 Hz, 1H, NCH=C(OEt)CH=CHCH$_2$), 7.48 (s, 1H, NCH=C(OEt)CH=CHCH$_2$).

Reaction of ethyl isonicotinate with $PhMeSiH_2$ in the presence of Cp_2TiMe_2

$PhMeSiH_2$ (0.26 mL, 1.91 mmol) and ethyl isonicotinate (0.13 mL, 0.95 mmol) were added to Cp_2TiMe_2 (10 mg, 0.05 mmol). The solution color became dark blue then brown over the course of 3 h. It was then stirred at 80°C for a further 36 h. Near-quantitative conversion the ethyl nicotinate to a mixture of 4-picoline and the silylether **6** (ratio 1:5) was observed by ^1H NMR. ^1H NMR (200 MHz, benzene-d_6, 22°C) δ: 0.35 (s, 3H, $SiCH_3$), 1.15 (t, 3H, OCH_2CH_3), 3.7 (q, 2H, OCH_2CH_3), 4.61 (m, 2H, CH_2O), 6.8–8.5 (m, 9H, PhH and the H on the pyridine ring).

Reactions of ethyl 2-methylnicotinate and methyl 6-methylnicotinate with $PhMeSiH_2$ in the presence of Cp_2TiMe_2

Ethyl 2-methylnicotinate and $PhMeSiH_2$ were reacted under the same conditions as ethyl isonicotinate and similar color changes occurred during the raction. The mixture was stirred at room temperature for 24 h. Quantitative conversion to 2,3-lutidine and **7** (ratio 2:3) was observed in 5 h by ^1H NMR. ^1H NMR of **7** (200 MHz, benzene-d_6, 22°C) δ: 0.35 (s, 3H, $SiCH_3$), 1.15 (t, 3H, OCH_2CH_3), 2.40 (s, 3H, Me on the ring), 3.7 (q, 2H, OCH_2CH_3), 4.60 (m, 2H, CH_2O), 6.7–8.6 (m, 8H, PhH and H's on the pyridine ring).

Under similar conditions, methyl 6-methylnicotinate gave a quantitative conversion to 2,6-lutidine and **8** (ratio of 1:4) by ^1H NMR. ^1H NMR for **8** (200 MHz, benzene-d_6, 22°C) δ: 0.37 (s, 3H, $SiCH_3$), 2.50 (s, 3H, Me on the ring), 3.40 (s, 3H, OCH_3), 4.65 (m, 2H, CH_2O), 6.6–8.0 (m, 8H, PhH and H's on the pyridine ring)].

Relative rates of reaction of pyridine, 3-picoline, 4-picoline, 3,5-lutidine, and ethyl nicotinate with Cp_2TiMe_2 and $PhMeSiH_2$

In separate Schlenk reactors, pyridine (0.35 mL, 4.6 mmol), 3-picoline (0.45 mL, 4.6 mmol), 4-picoline (0.45 mL, 4.6 mmol), 3,5-lutidine (0.48 mL, 4.6 mmol), and ethyl nicotinate (0.67 mL, 4.6 mmol) were added to a mixture of Cp_2TiMe_2 (0.09 g, 0.43 mmol) and $PhMeSiH_2$ (0.89 g, 6.5 mmol) together with 50 μL of $SiEt_4$ (in the case of pyridine 0.13 mL of C_6D_6 was also added). The mixtures were stirred at room temperature. NMR samples were extracted periodically by syringe. The conversions were calculated based on the comparison of integrals.

Reaction of pyridine-d_5 with H_2 catalyzed by Cp_2Ti-H

Pyridine-d_5 (0.30 mL, 3.94 mmol) was added to a solution of Cp_2Ti-H (50 mg, 0.28 mmol in 1 mL toluene-d_8, containing a known concentration of Me_4Si as calibrant) in a miniature stirred pressure reactor. The mixture was held at 400 psi H_2 and 80°C for 10 h. Analysis by ^1H NMR showed <10% of the pyridine was hydrogenated, but >90% of the D at the 2- and 6-positions was exchanged with H.

Reaction of $CpCp^*TiMe_2$, pyridine, and $PhSiH_3$

A 5 mm NMR tube was charged with $PhSiH_3$ (30 μL, 0.24 mmol), $CpCp^*TiMe_2$ (20 mg, 0.07 mmol), pyridine (11 μL, 0.14 mmol), and benzene-d_6 (0.4 mL). After thorough mixing, the solution was left to stand at room temperature. It very slowly turned green and after 4 days the ^1H NMR spectrum only showed resonances assignable to the following compounds: *N*-(phenylsilyl)-2,3,4-tetrahydropyridine; ^1H NMR (200 MHz, benzene-d_6, 22°C) δ: 1.52 (m, 2H, $NCH_2CH_2CH_2CH$=CH), 1.92 (m, 2H, $NCH_2CH_2CH_2CH$=CH), 2.96 (m, 2H, $NCH_2CH_2CH_2$ CH=CH), 4.99 (s, 2H, SiH_2), 6.22 (m, 1H, $NCH_2CH_2CH_2CH$=CH), 6.64 (m, 1H, $NCH_2CH_2CH_2CH$=CH), 7.14 (m, 3H, *m*-, *p*-C_6H_5), 7.42 (m, 2H, *o*-C_6H_5). *N*-(phenylmethylsilyl)-2,3,4-tetrahydropyridine, $PhMeSiH_2$, $PhMe_2SiH$, and CH_4. The *N*-(phenylsilyl)-2,3,4-tetrahydropyridine and *N*-(phenylmethylsilyl)-2,3,4-tetrahydropyridine formed in a ratio of 4:1. No CpCp*Ti species were observed in the NMR spectra, probably because of paramagnetism.

Acknowledgments

Financial support from the NSERC of Canada and the Fonds FCAR du Québec are gratefully acknowledged.

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