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A Highly Efficient Base-Metal Catalyst: Chemoselective Reduction of Imines to Amines Using An Abnormal-NHC–Fe(0) Complex

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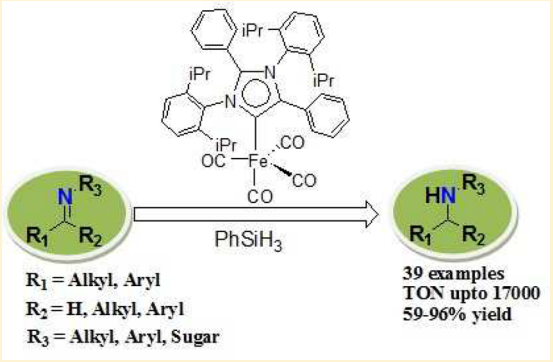
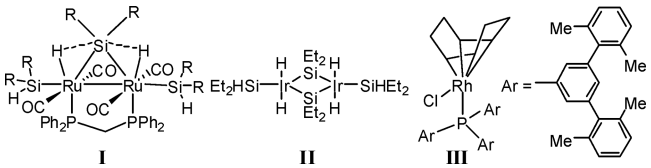
Supporting Information

ABSTRACT: A base-metal, Fe(0)-catalyzed hydrosilylation of imines to obtain amines is reported here which outperforms its noble-metal congeners with the highest TON of 17000. The catalyst, (*a*NHC)Fe(CO)$_4$, works under very mild conditions, with extremely low catalyst loading (down to 0.005 mol %), and exhibits excellent chemoselectivity. The facile nature of the imine reduction under mild conditions has been further demonstrated by reducing imines towards expensive commercial amines and biologically important N-alkylated sugars, which are difficult to achieve otherwise. A mechanistic pathway and the source of chemoselectivity for imine hydrosilylation have been proposed on the basis of the well-defined catalyst and isolable intermediates along the catalytic cycle.



Amines are ubiquitously present in a wide variety of chemicals, including natural products, agrochemicals, pharmaceuticals, and biologically active compounds.[1] The importance of amines in biological processes is further emphasized by their very frequent occurrence in different alkaloids, amino acids, and nucleotides. Owing to the widespread use of amines, the development of novel methods toward their effective and economical preparation is a highly desirable goal in catalysis research. For their preparation, the catalytic hydrosilylation of nitriles, amides, imines, and nitroarenes[2] and reductive amination[3] are among the very few commonly practiced methods. Despite some sporadic reports of transition metal catalyzed reduction of imines by hydrogenation,[4] hydrogen transfer,[5] or hydrosilylation,[6] a well-performing catalyst to achieve this important transformation is still missing and hence highly coveted. The few reported catalysts for imine reduction are heavily dominated by rare, expensive, and toxic late transition metal complexes (Chart 1).[7] Some notable recent examples of catalytic hydrosilylation of imines using late transition metals include the (μ-silane)-diruthenium complex **I** by Kira,[7a] silylene-bridged iridium dimer complex **II** by Brookhart[7b] and also the bowl-shaped phosphine complex of rhodium **III** by Tsuji[7c] (Chart 1). Consequently, an inexpensive and environmentally benign transition-metal surrogate, replacing scarce, toxic, and expensive transition metals, is a pressing need.[8] In this direction, the use of normal N-heterocyclic carbenes (*n*NHCs) has shown promise in designing base-metal catalysts for imine reduction.[9] Despite some interesting reports on iron-catalyzed hydrosylilation,[9a,10] there is a significant lack of very active iron-based catalysts which can in particular reduce ketimine at room temperature.

Chart 1. Examples of Transition-Metal Catalysts Used for Hydrosilylation of Imines



Recently N-heterocyclic carbene and its close analogues heralded a new era in base-metal catalysis and have enjoyed a significant research focus.[11] Crabtree and Bertrand have pioneered the abnormal binding modes of N-heterocyclic carbenes, which are proved to be even a better σ donors in comparison to their classical normal NHC analogues.[12] In the past few years, we have established that the isolated abnormal NHC (*a*NHC) is an exceptional ligand for designing useful organic[13] as well as organometallic catalysts[14] for a broad variety of organic transformations. Additionally, we were motivated by the fact that, despite some sparse reports of *a*NHC-based iron complexes,[15] the catalytic activity of such complexes thus far has not been thoroughly investigated. To the best of our knowledge, a single report has been documented by Darcel and co-workers involving a cyclopentadienyliron(II)–normal NHC complex which works

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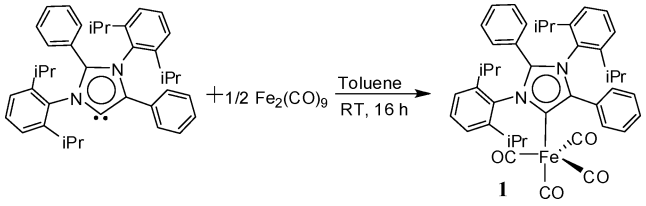
for the reduction of ketimines at higher temperature (100 °C).[9a] We surmised that the superior σ-donor ability of *a*NHCs may make the low-valent Fe(0) center sufficiently electron rich so that oxidative addition of the silane can be easily achieved, and this prompted us to use an (*a*NHC)Fe complex. We also anticipated that the combination of electron-rich Fe(0) with a strong σ donor *a*NHC ligand can work under very mild conditions, which may allow the synthesis of an array of amine-containing biologically important molecules that are usually sensitive to harsh reaction conditions. Thus, in our pursuit for a better iron catalyst, we report an elegant example of an iron(0) complex, [(*a*NHC)Fe(CO)$_4$] (**1**), which has a tremendous potential for efficient hydrosilylation of imines at room temperature with excellent chemoselectivity. The catalyst can convert a plethora of imines into amines with an extremely low catalyst loading of 0.05 mol %. This extremely low catalyst loading leads to an impressive TON of 17000, effectively outperforming all of the previous catalysts reported for imine hydrosilylation.[2f,9a] More encouragingly, this is a relatively rare entry where such a reactive system also demonstrate excellent selectivity in reducing imine functionalities in the presence of other commonly reducible carbonyl, cyano, and nitro motifs. Such a combination of efficiency and selectivity in imine reduction prompted us to reduce imines connected to sugar moieties, resulting in biologically relevant N-alkylated sugars, which are difficult to synthesize otherwise.

RESULTS AND DISCUSSION

Synthesis and Characterization. The synthesis of **1** was accomplished by the treatment of free *a*NHC with commercially available diiron nonacarbonyl [Fe$_2$(CO)$_9$]) in a 2:1 stoichiometric ratio in toluene at room temperature (Scheme 1). Analytically pure pale yellow crystals of **1** were

Scheme 1. Synthesis of Complex 1



obtained in 52% isolated yield from a concentrated toluene solution at −21 °C. Compound **1** readily dissolves in toluene, benzene, and THF and shows somewhat limited solubility in hexane and pentane.

The nature of the complex has been probed by an array of spectroscopic means (^{1}H and ^{13}C NMR and IR spectroscopy), as well as by CHN analysis and single crystal X-ray diffraction studies. The ^{13}C NMR spectrum of **1** reveals a resonance at 218.2 ppm, assignable to the C-5 carbon bound to the iron center which is expectedly shifted downfield from the corresponding chemical shift of free *a*NHC.

To ascertain the bond connectivities, a medium sized crystal was analyzed via single crystal X-ray diffraction (Figure 1).[16] Compound **1** crystallizes in the triclinic space group $P\bar{1}$ with a single molecule in the asymmetric unit. As expected, the X-ray crystal structure of **1** exhibits an iron(0) trapped in a distorted-trigonal-bipyramidal environment and bonded to the *a*NHC and four carbonyl moieties. The Fe−C$_{carbene}$ bond distance is

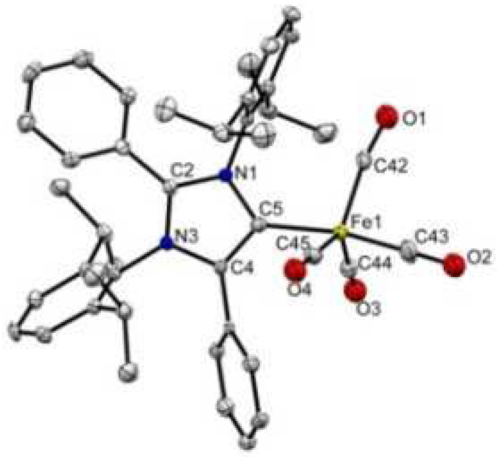


Figure 1. View of the molecular structure of **1**. Ellipsoids are set at the 50% probability level; hydrogen atoms have been omitted for clarity. Selected bond distances (Å) and angles (deg): Fe1−C5, 2.026(3); Fe1−C42, 1.796(4); Fe1−C45, 1.770(4); Fe1−C44, 1.757(4); Fe1−C43, 1.745(4); C42−Fe1−C5, 101.84(14); C45−Fe1−C5, 85.28(15); C43−Fe1−C5, 169.71(16), C44−Fe1−C5, 84.82(15).

2.026(3) Å, comparable to that in [(NHC)Fe(CO)$_4$],[17a] as analyzed crystallographically.

After analyzing the structure by X-ray crystallography, we used **1** as a catalyst for hydrosilylation reactions of imines. Given the industrial importance of 1-aryl ethylamines, hydrosilylation of *N*-benzylideneaniline as an aldimine partner was chosen as a model substrate for this study with PhSiH$_3$ as a silylating agent. Gratifyingly, the reaction went smoothly at room temperature to realize 95% conversion to the corresponding amine in ethanol. Upon further optimization, full conversion (>99%) was achieved in DMSO with a catalyst loading of as low as 0.05 mol %. The role of the catalyst **1** in the silylation of imines is eminent, as in a blank reaction no product was detected by ^{1}H NMR spectroscopy even at higher temperature (Table S1, entry 23, in the Supporting Information). We tested various silanes, including cheaper silanes such as PMHS and (TMSO)$_2$SiMeH. PMHS can be used successfully, but it gave a good yield (around 70%) only when it was used in excess (10 equiv), while the use of 2 equiv of (TMSO)$_2$SiMeH resulted in good to moderate yield (see Table 1, entry 25 and Table S1). Among a variety of silanes tested, PhSiH$_3$ was the best, although other silanes provided moderate conversion to silylated amines. Strikingly, the catalyst can also perform with extremely low loading (0.005 mol %) at room temperature, leading to a considerably high TON value of 17000, albeit with slightly lower yield (85%).

Substrate Scope of Aldimines. With the optimized reaction conditions in hand (Table S1, entry 16, in the Supporting Information), we investigated the scope of the reduction of various aldimines (**2**) to their corresponding secondary amines (**3**) (Table 1). Under the standardized conditions, the presence of an electron-donating group at the para and ortho positions of the aniline moiety afforded high yields (78−92%) (Table 1, entries 2−4). Under similar conditions, benzylidene moieties containing both electron-donating and -withdrawing substituents at the para position of benzylidene offered a nearly quantitative yield of the corresponding amines (Table 1, entries 5−10). Moreover, the reduction was effective without any dehalogenations evidenced from the substrates containing chloro, bromo, and iodo groups

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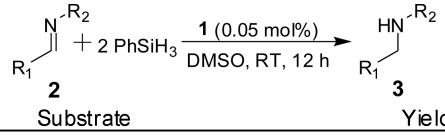
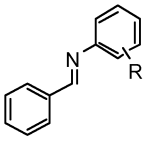
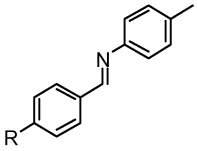
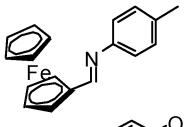
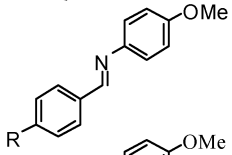
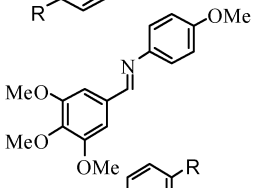
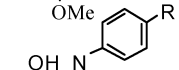
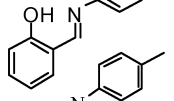
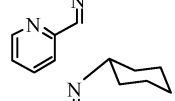
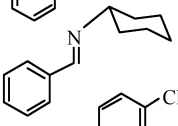
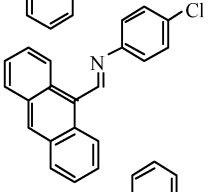
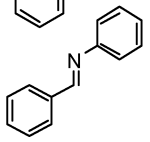
Table 1. Hydrosilylation of Various Aldimines Catalyzed by 1[a]



Entry	Substrate		Yield (%)[b]
1		R = H	96
2		R = p-Me	92
3		R = o-Me	78
4		R = p-OMe	90[d]
5		R = Me	95
6		R = OMe	96
7		R = NMe_2	93
8		R = I	95
9		R = Br	95
10		R = Cl	94
11		R = CN	95[c]
12		R = NO_2	85[c]
13		R = $COCH_3$	92[d]
14		R = CO_2CH_3	85
15			95
16		R = CN	92[c]
17		R = NO_2	80[c]
18			96
19		R = H	91
20		R = CO_2H	85
21			77
22			93
23			59[d]
24			95
25			63(66)[e]

[a]Reaction conditions unless specified otherwise: aldimine (0.5 mmol), $PhSiH_3$ (1 mmol), and complex **1** (0.05 mol %), DMSO (1 mL), room temperature, 12 h. [b]Isolated yield. [c]Complex **1** (0.2 mol %), 50 °C. [d]Conversion by ^1H NMR spectroscopy. [e]63% and 66% ^1H NMR spectroscopic conversions with PMHS (10 equiv) and $(TMSO)_2SiMeH$ (2 equiv), respectively.

(Table 1, entries 8–10). Substrates with highly electron withdrawing groups, such as 4-cyano- and 4-nitrobenzylidene derivatives, also afforded excellent isolated yields (85–95%) with slightly high catalyst loading (0.2 mol %) and at elevated temperature (50 °C) (Table 1, entries 11 and 12). Most notably, the catalyst is considerably selective toward reduction of imine in the presence of various carbonyl groups such as ketone and ester at the 4-position of benzylidene, providing excellent yields (85–92%) of the expected amine products (Table 1, entries 13 and 14). In the presence of heavily electron deficient groups such as 4-nitro and 4-cyano on the benzylidene moiety, amine products were also furnished in excellent yield (Table 1, entries 16 and 17). The catalyst can also perform very well in the presence of an electron-rich substituent, as the reaction with a 3,4,5-trimethoxy-substituted benzyl substrate went smoothly to 96% isolated yield of *N*-(3,4,5-trimethoxybenzyl)-4-methoxyaniline (Table 1, entry 18). Gratifyingly, this hydrosilylation methodology proved fruitful in synthesizing biologically active amines in high yields, which are prohibitively expensive from commercial sources (for entry 19, 50 mg costs $670),[18] arguably due to the dearth of elegant synthetic methods (Table 1, entries 19 and 20). The catalyst's chemoselectivity was further demonstrated by the reduction of aldimine in the presence of a C=C bond, leading to the corresponding unsaturated amine with good conversion, retaining the nonreduced double bond (Table 1, entry 21). Our exploration for substrate scope was further expanded to heteroaromatic imines, which were reduced well to offer potentially good bidentate ligands (Table 1, entry 22). The catalytic efficiency was also surveyed in the presence of *N*-cyclohexylamine and anthracen-9-ylmethylene moieties to give their corresponding amines in moderate to very good yield (59–95%) (Table 1, entries 23 and 24).

Since complex **1** proved itself as an extremely active catalyst for aldimine reduction, we were also curious to test its catalytic efficacy in hydrosilylation reactions of more challenging substrates such as ketimines (**4**). Optimization of the best conditions of ketimine reduction involves slightly higher catalyst loading (2 mol %) in ethanol with a longer reaction time, owing to the increased steric congestion and attenuated electrophilicity of the ketimine (Table S2, entry 9, in the Supporting Information). To check the catalytic strength of complex **1**, we choose 4-methyl-*N*-[1-(4-methylphenyl)-ethylidene]aniline as a model substrate for ketimine hydrosilylation reactions.

Substrate Scope of Ketimines. To further survey the substrate scope for such reduction, ketimines were chosen accordingly, bearing electron-rich as well as electron-deficient groups at the 4-position of the ethylidene moiety. A quantitative yield was obtained for such reduction reactions to the corresponding secondary amines (Table 2, entries 1–4). Under similar reaction conditions, an electron-donating group at the para position of aniline, the ortho position of ethylidene, and also an electron-withdrawing group at the 4-position of acetophenone leads to the desired products in a promising isolated yield (85–95%) (Table 2, entries 5–7). However,

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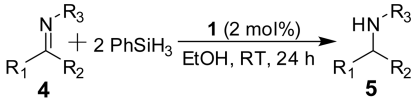
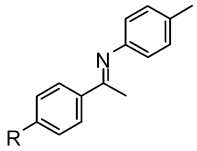
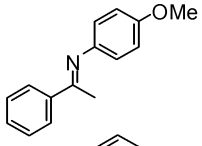
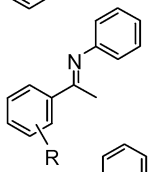
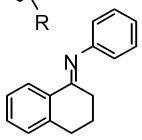
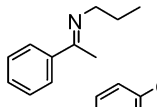
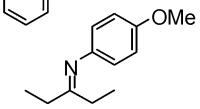
Table 2. Hydrosilylation of Various Ketimines Catalyzed by 1[a]



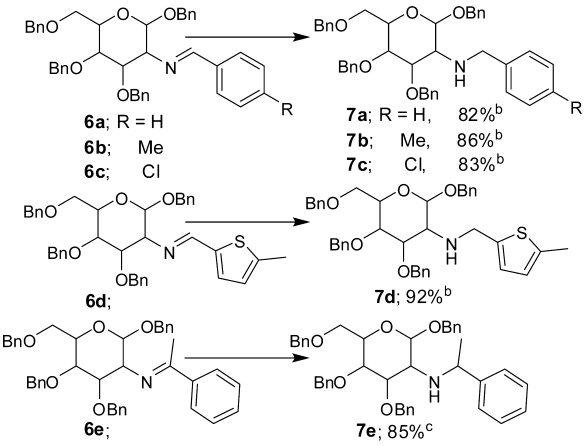
Entry	Substrate		Yield (%)[b]
1		R = H	95
2		R = Me	89
3		R = Br	87[c]
4		R = CF_3	87
5			95
6		R = p-CF_3	85
7		R = o-Me	93
8			91
9			85[c]
10			93[c]

[a]Reaction conditions: ketimine (0.5 mmol), $PhSiH_3$ (1 mmol), complex **1** (2 mol %), ethanol (1 mL), room temperature, 24 h. [b]Isolated yield. [c]Conversion by ^1H NMR spectroscopy.

further tests of functional group tolerance in the presence of reducible groups such as $-NO_2$ and $-CN$ resulted in poor conversion (~15%) to the corresponding amine products. From these observations, it can possibly be inferred that steric hindrance on the ethylidene moiety does not play a large role in these reactions. It is noteworthy that the more challenging substrates having an alkyl group in the ethylidene as well as in amine moieties led to the expected reduction products in an excellent isolated yield (85−93%, Table 2, entries 8−10).

Substrate Scope of Imines Bearing Sugar Moieties. Our success in reducing multifarious aldimines and ketimines by **1** under mild conditions prompted us to test the catalyst further for reduction reactions in the presence of sugars. Sugar derivatives are important precursors for biologically relevant compounds such as glycosidase inhibitors, GlcN-6-P synthase inhibitors, etc.[19] It has been shown previously that strong GlcN-6-P synthase inhibitory properties and good antifungal activities were achieved by the introduction of *N*-alkyl derivatives to 2-amino-2-deoxy-D-glucose.[20] In the synthesis of this *N*-alkylated sugar derivative, direct alkylation of 2-amino-2-deoxy-D-glucose has been proven to be very difficult and crumbersome.[21] To overcome this problem, we have introduced hydrosilylation for the preparation of *N*-alkyl derivatives of 2-amino-2-deoxy-D-glucose. As presented in Scheme 2, hydrosilylations of 1,3,4,6-tetra-*O*-benzyl-2-(*N*-benzylidene)-2-deoxy-β-D-glucose derivatives run smoothly

Scheme 2. Hydrosilylation of Imines Bearing Sugar Derivatives[a]



[a]Reaction conditions: imines (0.5 mmol), $PhSiH_3$ (1 mmol), and complex **1** (0.2 mol % for **6a−d** and 1 mol % for **6e**), DMSO (1 mL) for **6a−d** and EtOH (1 mL) for **6e**, room temperature, 16 h. [b]Isolated yield. [c]Conversion by ^1H NMR spectroscopy.

with only 0.2 mol % of catalyst **1** loading. Several other sugar derivatives of the imine can also be effectively reduced to obtain the corresponding *N*-alkylated sugars in low catalyst loadings, proving this reduction to be very mild and tolerant to sensitive protections. Interestingly, when a sugar-containing heterocyclic ring in the imine moiety was subjected to hydrosilylation, a 92% yield of the corresponding amine product **7d** was obtained at room temperature. However, our catalytic protocol did not work for unprotected sugar substrates containing free OH functionalities. We note in passing that the imine reduction methodology in protected sugars to prepare valuable *N*-alkylated sugars closely resembles the in situ reduction of imines during alcohol to amine direct coupling by borrowing the hydrogen strategy developed by Feringa and Barta.[22] In their presented catalytic cycle, an alcohol is dehydrogenated to the respective carbonyl compound, which upon reaction to amine forms an imine, before being reduced by the trapped hydrogen in the presence of an iron catalyst. Beller's primary amine synthesis from secondary alcohols using ammonia with a ruthenium catalyst[23] also indicates the intermediacy of an imine.

Chemoselectivity of the Reduction Process. Our initial findings presented in Tables 1 and 2 demonstrated that the catalyst **1** not only is highly reactive but also can spare a number of functional groups during the catalytic process, leading to excellent chemoselectivity. The chemoselectivity of the catalyst **1** is evident from the reduction of aldimines possessing a nitrile, nitro, ketone, ester, acid group and an unsaturated double bond (Table 1, entries 10−13, 15, 16, 19, and 20). To our delight, in all cases these aldimines were selectively reduced without affecting the presence of other highly reducible groups. The only detrimental effect of introducing an electron-withdrawing group in the aldimine was the decelerated reaction rate. The excellent chemoselectivity in the reduction of imines was further scrutinized by performing the catalytic reaction in the presence of an 1:1 mixture of an imine and the corresponding aldehyde or ketone,

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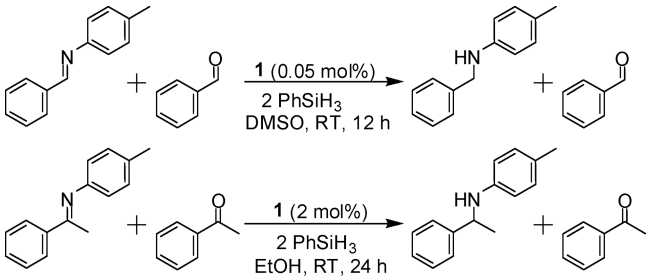
which resulted in a clean reduction of only imines, leaving the aldehyde or ketone intact (Scheme 3). This is in contrast to the

Scheme 3. Chemoselective Reduction of Imines into Amines in the Presence of an Aldehyde or Ketone[a]

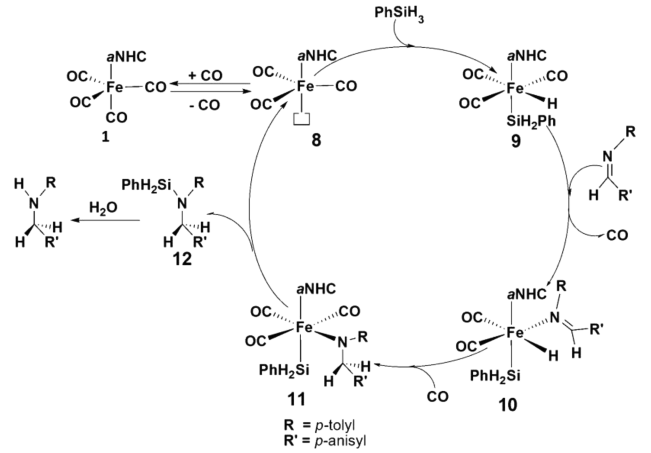


[a]The corresponding alcohol was not obtained from aldehyde or ketone reduction in absence of aldimine or ketimine.

fact that a less reactive catalyst, $(IMS)Fe(CO)_4$, reduces benzaldehyde at room temperature, but we attribute this fact to the remarkable selectivity of our catalyst. To further understand the source of such chemoselectivity, we resorted to high-level DFT calculations (vide infra).

Mechanistic Understanding. The remarkable activity of **1** as a catalyst for the efficient hydrosilylation of imines inspired us to uncover the mechanistic details of the above reaction. To develop a clear picture for some of the intermediates en route to the product formation, we investigated the detail via stoichiometric reactions. At first, the catalyst **1** requires activation by extruding one of the strongly π acidic CO ligands, where the vacant site may facilitate the oxidative addition of the silane. Upon CO loss, activated **8** is prone to oxidatively add $PhSiH_3$ to generate an iron hydride species along with a coordinated silyl ligand (Scheme 4). The resulting hydride

Scheme 4. Plausible Catalytic Cycle for the Hydrosilylation of Imines Catalyzed by Complex 1



intermediate species **9** is irrevocably identified from its diagnostic ^1H NMR chemical shift at −9.22 ppm ($^3J_{H,H}$ = 1 Hz) along with the silyl hydrogen resonances at 5.36 ppm. A very similar upfield shift for the Fe hydride (−8.74 ppm)[17a] that has been reported earlier for an analogous complex comprising a classical carbene supports our assertion further. The low-spin Fe hydride complex **9** is unstable, denying us from crystallizing it despite multiple attempts. The lack of crystallographic characterization for the elusive **9** prompted us to scrutinize it computationally. The computationally optimized (B3LYP/LanL2DZ(Fe)/6-31G*(H,C,N,O,Si) level of theory)[24] structure (slightly truncated model) clearly exposes the hydride group with an Fe−H distance of 1.53 Å (Figure 2), closely

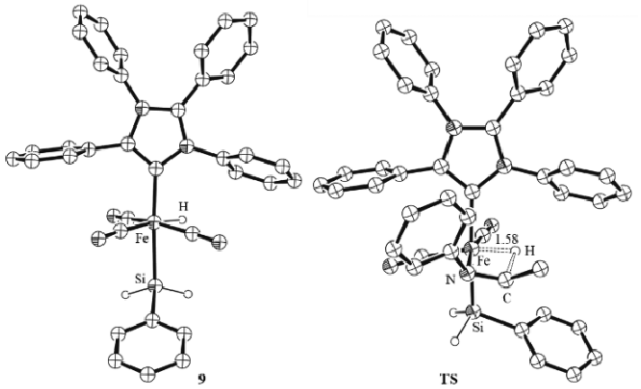


Figure 2. Computationally optimized structure of intermediate **9** and the **TS** for hydride insertion to the imine. All hydrogens except for the iron hydride and the silyl hydrogens have been omitted for clarity.

resembling the Fe−H distances (1.43 and 1.46 Å) in $(IMes)Fe(H)(SiPh_3)(CO)_3$ and $(PMe_2Ph)Fe(H)(SiPh_3)(CO)_3$ as crystallographically characterized by Darcel.[17a] Additionally, the theoretically derived value of the NMR shielding tensor, −5.43 ppm, by gauge-independent atomic orbital (GIAO) calculations for the iron hydride correlates well with the experimentally observed value.[25] The intermediate **9** was further characterized by ^{29}Si NMR spectroscopy, displaying a resonance at −6.07 ppm, as well as carbonyl stretches at 2003, 1963, and 1893 cm^{-1} by IR spectroscopy (Figures S37 and S38 in the Supporting Information). These CO stretches are observed at higher frequencies γ_{CO} : 2003, 1963, and 1893 cm^{-1} in comparison to the stretches from **1** γ_{CO} : 1998, 1912, and 1871 cm^{-1}, corroborating that the iron center has reached the +2 oxidation state upon oxidative addition. Ideally, the ease of oxidative addition of Fe(0) to Fe(II) should be facilitated by an electron-rich metal center. To check this possibility, we compared the head to head catalytic activity of an Fe(0) complex bearing a normal NHC and compared it with that of the present abnormal NHC bound Fe(0) catalyst in the hydrosilylation of imines. Accordingly, the *n*NHC−Fe(0) complex $[(IPr)Fe(CO)_4]$[17c] was employed for the hydrosilylation of two aldimines, 4-chlorobenzylidene-4-methylaniline and 4-methylbenzylidene-4-methylaniline, furnishing 27% and 43% yields of the corresponding amines, respectively, under reaction conditions identical with those adopted for catalyst **1**. An analogous probe for ketimine hydrosilylation using 4-methyl-*N*-(1-*p*-tolylethylidene)aniline as a test substrate resulted in only a 35% yield of the corresponding amine. Both the aldimine and ketimine reductions described above prove irrefutably that our catalyst **1** performs significantly better (yields 94%, 95%, and 89%, respectively; see Table 1, entries 5 and 10, and Table 2, entry 2) than its classical normal carbene congener. We attribute this effect to the better σ-donor ability of *a*NHC in comparison to *n*NHC, which will make the iron(0) center more electron rich to facilitate oxidative addition of the silane. Indeed, close analysis of the Tolman electronic parameter[26] clearly affirms our hypothesis. In the case of **1**, the γ_{CO}(A1) mode was observed at 1998 cm^1, which is

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considerably lower than 2035 cm^{-1}, seen for $[(IPr)Fe(CO)_4]$. This lower stretching frequency of the specific mode can clearly be attributed to the enhanced π back-donation to the low-lying π^* orbital of CO, in the case of **1**, owing to the greater σ donation of the *a*NHC. Moreover, theoretically calculated CO stretching frequencies for the γ_{CO} band of **1** (2003 cm^{-1}) are fully consistent with the above ($[(IPr)Fe(CO)_4]$, 2015 cm^{-1})[27] trend.

In the intermediate **10** (Scheme 4), the imine substrate binds to the iron center upon further creation of a vacant site by removing CO from **9**. The excellent chemoselectivity in imine reduction elicited by **1** (vide supra) most likely lies in the preferential binding of an imine functionality to the iron center. As probed computationally, binding of the imine group in 4-acetyl-*N*-(1-phenylbenzylidene)aniline is favored over the carbonyl binding by 5.69 kcal mol^{-1} (see Figure 3). Exactly

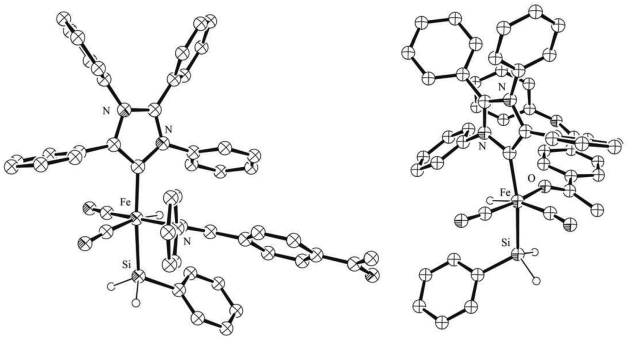

Figure 3. Computationally optimized structures of two binding modes of imine (left) vs carbonyl to Fe^{II} (right). Imine binding is favored by 5.69 kcal mol^{-1} over the carbonyl binding mode. All hydrogens except for the iron hydride and the silyl hydrogens have been omitted for clarity.

the same trend is observed for other aldimine substrates containing aldehyde and ester functionalities, where binding of imine is distinctly preferred over aldehyde or ester binding by 4.64 and 16.94 kcal mol^{-1}, respectively, providing further support to this hypothesis. The imine is subsequently inserted by a hydride migration. Computationally, we were able to locate the transition state (**TS**) for imine insertion, which poses a free energy barrier of 21.6 kcal mol^{-1}, with respect to the imine-bound intermediate **9**. After the insertion, reductive elimination ensues, traverses through a barrier of 13.5 kcal mol^{-1} to liberate the silylamine product, and reverts back to the catalyst at the Fe(0) stage. Overall, our proposed mechanism follows the classic Chalk−Harrod pathway of hydrosylilation,[28] where oxidative addition of the silane and hydride migration to insert the imine are the two key steps. Notably, the pivotal role of the Fe hydride species **9** in the catalytic cycle is unambiguously established by its stoichiometric reaction with *N*-(4-methoxybenzylidene)-4-methylaniline in DMSO-d_6 at slightly elevated temperature, in which the hydride resonance vanishes completely to form **11**, as traced by ^{1}H NMR spectroscopy. In our case, the alternative pathway of silyl migration to incorporate imine (as opposed to hydride migration) can be easily refuted, as the benzylic protons, obtainable through hydride migration in the reduced imine, are clearly displayed at 4.13 ppm in the ^{1}H NMR spectrum (see the Supporting Information). Of note, the well-defined catalyst molecule **1** and isolable intermediate **9** inarguably help in gathering convincing data to delineate the plausible mechanism for imine reduction.

CONCLUSIONS

In conclusion, we have developed an efficient *a*NHC based iron(0) catalyst, which can selectively hydrosilylate various aldimines and ketimines under remarkably low catalyst loadings at room temperature with significantly high turnover numbers (up to 17000). Since the catalysis occurs under very mild conditions, the reduction can encompass a wide range of imine substrates with considerable functional group tolerance, leading to excellent chemoselectivity. Moreover, this catalyst exhibits superior performance for the hydrosilylation of highly functionalized imine substrates derived from sugars, to provide straightforward access to their *N*-alkylated derivatives, which have not been obtained earlier under mild conditions. In addition, the present catalyst delivered excellent yield to commercially available and expensive hydroxyl-functionalized amines, which are difficult to achieve otherwise. A combined experimental and theoretical investigation discloses that the imine hydrosilylation reaction proceeds through the formation of iron hydride complex **9** followed by hydride migration to insert imines. The excellent σ-donating ability of the *a*NHC ligand helps the iron center to be sufficiently electron rich so that it can outperform its classical regular NHC congeners in hydrosilylation reactions. Encouragingly, the observed catalytic activity for the base-metal iron complex is even superior to that of reported noble-metal catalysts used for hydrosilylation of imines.

EXPERIMENTAL SECTION

Methods. The ligand *a*NHC was prepared following the literature method,[12d] and the *n*NHC iron(0) complex $[(IPr)Fe(CO)_4]$ was prepared according to the literature procedure.[17c] The HRMS data were obtained using a Finnigan MAT 8230 instrument. Elemental analyses were carried out using a PerkinElmer 2400 CHN analyzer, and samples were prepared by keeping them under reduced pressure (10^{-2} mbar) overnight. The melting point was measured in a sealed glass tube on a Büchi B-540 melting point apparatus. Crystallographic data for the structural analysis of **1** have been deposited at the Cambridge Crystallographic Data Center (CCDC No. 1451782). These data can be obtained free of charge from the Cambridge Crystallographic Data Center. NMR spectra were recorded on a JEOL ECS 400 MHz spectrometer and on a Bruker Avance III 500 MHz spectrometer.

Synthesis of (*a*NHC)Fe(CO)$_4$ (1). In a glovebox, an oven-dried 50 mL Schlenk flask was charged with $Fe_2(CO)_9$ (200 mg, 0.55 mmol) and *a*NHC (541 mg, 1 mmol), and then dry toluene (25 mL) was added via cannula at 25 °C under an argon atmosphere. The reaction mixture was stirred overnight, and during the course of the reaction, the color changed to yellowish red. Then the reaction mixture was filtered through a Celite pad and concentrated further to ca. 8 mL. Storage of this reaction mixture at −20 °C for 2−3 days afforded yellow crystals (370 mg, 0.52 mmol, 52%). ^{1}H NMR (C_6D_6, 500 MHz, 298 K): δ 7.85 (d, 2H, J = 7.5 Hz), 7.36 (t, 1H, J = 7.5 Hz), 7.15 (s, 2H), 7.07 (t, 2H, J = 8 Hz), 6.95- 6.91 (m, 2H), 6.81 (d, 2H, J = 7.5 Hz), 6.76 (d, 2H, J = 8 Hz), 6.57−6.54 (m, 1H), 6.51−6.48 (m, 2H), 2.99 (sept, 2H, J = 6.5 Hz), 2.93 (sept, 2H, J = 6.5 Hz), 1.60 (d, 6H, J = 6.5 Hz), 0.99 (d, 6H, J = 7 Hz), 0.84 (d, 6H, J = 7 Hz), 0.69 (d, 6H, J = 6.5 Hz) ppm. ^{13}C NMR (C_6D_6, 125 MHz, 298 K): δ 218.2, 160.4, 146.6, 145.3, 144.8, 140.9, 136.6, 133.1, 132.3, 131.6, 131.1, 129.9, 129.6, 128.5, 128.4, 127.9, 127.5, 125.5, 125.2, 124.8, 29.2, 28.8, 24.4, 24.3, 23.8, 23.5 ppm. Anal. Calcd for $C_{43}H_{44}FeN_2O_4$: C, 72.88; H, 6.26; N, 3.95. Found: C, 72.72; H, 7.01; N, 3.90. IR (film; ν_{CO}, cm^{-1}): 1998, 1912, 1871.

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General Procedure for Catalytic Hydrosilylation of Aldimines. A Schlenk tube was charged with the catalyst **1** (0.00025 mmol, 0.177 mg (prepared from a standard solution of **1** in DMSO), 0.05 mol %), aldimine reagents (0.5 mmol), $PhSiH_3$ (1.0 mmol, 123.4 μL), and DMSO (1.0 mL) with a magnetic stirring bar in air. The reaction mixture was stirred at room temperature for 12 h. After the completion of the reaction, the reaction mixture was worked up with ether and water. The organic solvent was evaporated under vacuum, and the desired product was purified by column chromatography.

General Procedure for Catalytic Hydrosilylation of Ketimines. A Schlenk tube was charged with the catalyst **1** (0.01 mmol, 7.09 mg, 2.0 mol %), ketimine reagents (0.5 mmol), $PhSiH_3$ (1.0 mmol, 123.4 μL), and HPLC-grade ethanol (1.0 mL) with a magnetic stirring bar in air. The reaction mixture was stirred at room temperature for 24 h. After completion of the reaction, the reaction mixture was worked up with ether and water, the organic solvent was evaporated under vacuum, and the desired product was purified by column chromatography.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.organomet.6b00478.

Experimental procedures, spectroscopic data, scanned spectra, details of calculated structures, and X-ray crystallographic data for **1** (PDF)

Cartesian coordinates of calculated structures(XYZ)

X-ray crystallographic data for **1** (CIF)

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Notes

The authors declare no competing financial interest.

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(16) Crystal data for **1**: $C_{43}H_{44}FeN_2O_4$, M_r = 708.65, triclinic, space group $P\overline{1}$, a = 10.1393(8) Å, b = 10.7878(10) Å, c = 18.1314(15) Å, α = 77.341(8)°, β = 80.516(7)°, γ = 79.342(7)°, V = 1885.6(3) nm^3, Z = 4, ρ_{calc} = 1.248 Mg m^{-3}, μ(Mo Kα) = 0.443 mm^{-1}, T = 100(2) K, θ range for data collection 1.96−25.03°, R1 = 0.0529 ($I > 2\sigma(I)$), wR2 = 0.1225 (all data).

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