Doctoral Dissertation

Studies on the Iridium-Catalyzed Regioselective Silylation of Benzylic C-H Bonds in Azaarenes with Hydrosilanes

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Preface and Acknowledgements

The research presented in this thesis was carried out under the direction of Professor Naoto Chatani of the Department of Applied Chemistry, Faculty of Engineering, Osaka University between April 2012 and March 2018. The thesis is concerned with the development of the iridium-catalyzed direct silylation of $C(sp^3)$-H bonds at the α-position in alkylazaarenes.

This thesis would not have been possible without help, advice, and support from many people and I would like to express my sincerest appreciation to all of them.

First of all, I would like to express my utmost gratitude to Professor Naoto Chatani for the guidance and suggestions he provided throughout this work. His enthusiasm for chemistry has always motivated me. I respect him not only for his interest in chemistry but also for his personality.

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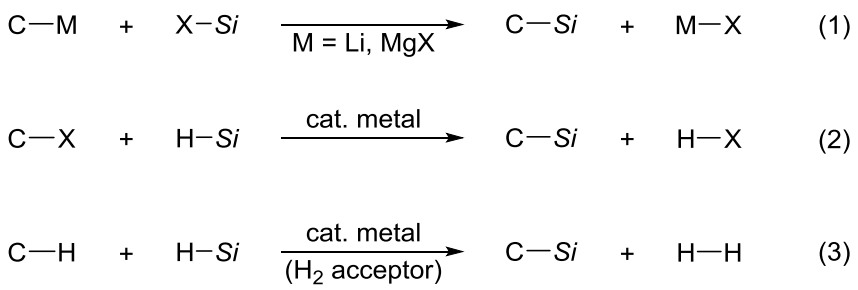
Masaya Hirano

Contents

General Introduction

Organosilicon compounds are one of the most important synthetic building blocks for a variety of chemical transformations[1] including Tamao-Fleming oxidation[2] and Hiyama cross coupling reactions.[3] The conventional method for C-Si bond formation involves the reaction of an organolithium or an organomagnesium reagent with a silyl halide (eq. 1 in Scheme 1). However, this approach suffers from the poor functional group tolerance owing to the use of highly reactive organometallic reagents and silicon electrophiles and the fact that substoichiometric amounts of metal salts are produced as wastes. Therefore, the transition metal-catalyzed cross-coupling reaction of C-X bonds with hydrosilanes was developed in an attempt to synthesize organosilicon compounds under mild reaction conditions with good functional group compatibility (eq. 2).[4] The catalytic direct silylation of C-H bonds, which are present ubiquitously in organic molecules, has recently emerged as one of the most useful and powerful methods in terms of atom- and step-economy (eq. 3).[4,5] Whereas a large number of the direct silylation of C(sp^2)-H bonds have appeared,[6] the corresponding reaction of C(sp^3)-H bonds has not been extensively developed. Especially, C(sp^3)-H/H-Si coupling reaction has been much less reported, compared to the intramolecular reaction to afford 5- or 6-membered silacycles.[7]

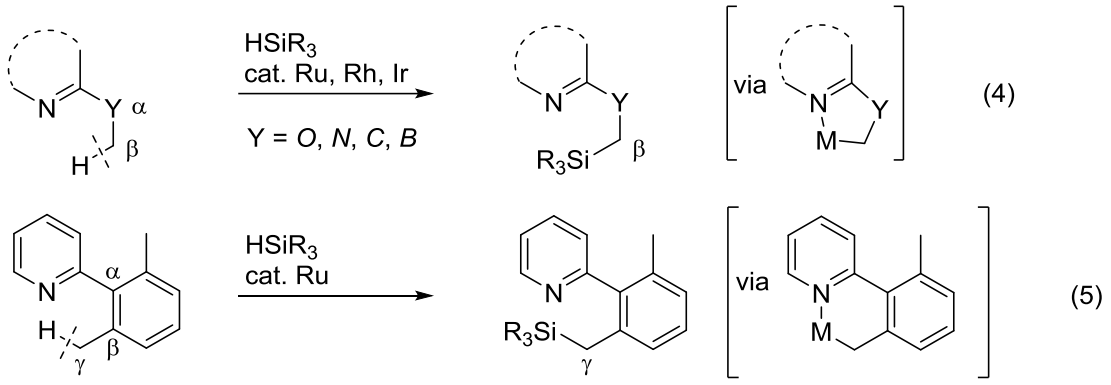
Scheme 1. Methods for C-Si Bond Formation



The chelation-assisted approach has been recognized as one of the more useful methodologies for the direct functionalization of C-H bonds,[8] and was also applied to the intermolecular C(sp^3)-H bond silylation.[9] The C(sp^3)-H bond is silylated regioselectively, due to guidance by a directing group, such as a pyridine ring.[10] However, chelation-assisted silylation was restricted to the C-H bonds at the β-position (eq. 4 in Scheme 2)[10b-f] and at the γ-position (eq. 5),[10a] which involve the formation of stable 5-membered or 6-membered metallacycles as key intermediates in the catalytic cycle. There have been no reports on the chelation-assisted silylation of C(sp^3)-H bond

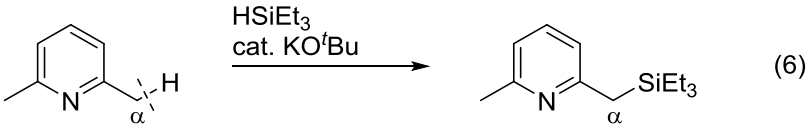
of substituents at the α-position (the benzylic position) in azaarenes, which requires the formation of a 4-membered metallacycle as an intermediate.

Scheme 2. Chelation-Assisted C(sp^3)-H Bond Silylation of the Substituent in Azaarenes at the β- and γ-Position



The KO^{t}Bu-catalyzed silylation of C-H bonds was recently reported,[11] which probably proceeded via a radical chain mechanism and/or a mechanism involving a pentacoordinated silicon species as a key intermediate.[12] This catalyst system enabled the C(sp^3)-H silylation of 2,6-dimethylpyridines at the α-position.[11b] However, the results for the silylation of other azaarenes were not described in the literature.

Scheme 3. KO^{t}Bu-Catalyzed C(sp^3)-H Bond Silylation in 2,6-Dimethylpyridines at the α-Position



Therefore, the development of new methods for the silylation of C(sp^3)-H bond is highly anticipated. The objective of this research was to develop new types of silylation of C(sp^3)-H bonds on substituents at the α-position in azaarenes via a new reaction mechanism. This thesis is composed of the following three chapters.

Chapter 1 contains a discussion of the $Ir_4(CO)_{12}$-catalyzed regioselective C(sp^3)-H bond silylation of 4-alkylpyridines at the benzylic position with hydrosilanes.

Chapter 2 deals with the $Ir_4(CO)_{12}$-catalyzed benzylic C(sp^3)-H bond silylation of 2-alkylpyridines with hydrosilanes.

Chapter 3 is concerned with the cationic-pincer iridium-catalyzed C(sp^3)-H bond silylation of

2-alkyl-1,3-azoles at the α-position in the alkyl group.

Finally, the findings are summarized in the conclusion section.

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Chapter 1

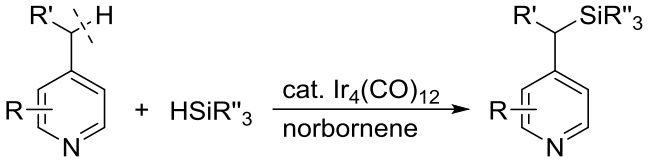
Iridium-Catalyzed Regioselective C(sp^3)-H Silylation of 4-Alkylpyridines at the Benzylic Position with Hydrosilanes Leading to 4-(1-Silylalkyl)pyridines

1.1 Introduction

Pyridines derivatives are among the most versatile structural motifs and are widely utilized in medicinal and material chemistry.[1] Thus, a variety of procedures for their efficient synthesis have been developed to date.[2] Transition metal-catalyzed direct C(sp^3)-H functionalization has also become a powerful tool for the introduction of new functional groups on a substituent, and a number of regioselective functionalizations of C(sp^3)-H bonds on substituents at the 2-position of the pyridine ring has been demonstrated.[3] A variety of catalytic α-C(sp^3)-H bond additions in 2-alkylpyridines to alkenes, alkynes, aldehydes, imines, and N-N double bonds in diethyl azodicarboxylate and catalytic α-C-H bond substitutions by allylic compounds and aryl halides have also been reported.[3a-b] However, only a few reports on the transformation of α-C(sp^3)-H bond in 4-alkylpyridines have been reported.[4] Furthermore, the catalytic α-C-H bond functionalization of polyalkylpyridine derivatives such as 2,4-dimethylpyridine with C4 selectivity is rare.[4g]

Chapter 1 describes the regioselective C(sp^3)-H silylation of 4-alkylpyridines with hydrosilanes in the presence of the iridium catalyst leading to the production of 4-(1-silylalkyl)pyridines (Scheme 1). As described in the general introduction, chelation-assisted silylation was restricted to the C-H bonds of C2-substituents in pyridines.[5] This reaction represents the first example of an iridium-catalyzed non-directed C(sp^3)-H bond silylation with a hydrosilane.

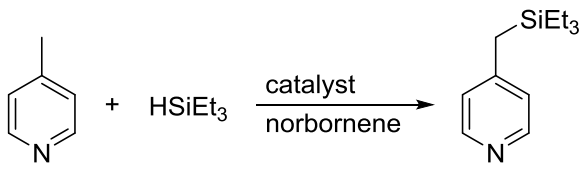
Scheme 1. Iridium-Catalyzed Regioselective C(sp^3)-H Silylation of 4-Alkylpyridines at the Benzylic Position with Hydosilanes



1.2 Results and Discussion

Optimization of reaction conditions was initiated by examining the coupling of 4-methylpyridine (**1a**, 1 mmol) and triethylsilane (2 mmol) using an iridium catalyst as shown in Table 1. To my delight, $Ir_4(CO)_{12}$ was found to promote the coupling reaction in toluene at 80 ºC for 20 h to produce 4-[(triethylsilyl)methyl]pyridine (**2a**) in 26% yield, along with 40% of **1a** being reaovered (entry 1). As is the case with previously reported C-H/H-Si coupling reactions,[5] the addition of norbornene to the reaction of **1a** as a hydrogen scavenger improved the yield of **2a** to 85%. **2a** was isolated in 79% yield by column chromatography on NH_2-modified silica-gel (entry 2). In this reaction, no C(sp^2)-H bond silylation products were detected at the 2- or 3-positions on the pyridine ring.

Table 1. Catalyst Screening[a]



1a **2a**

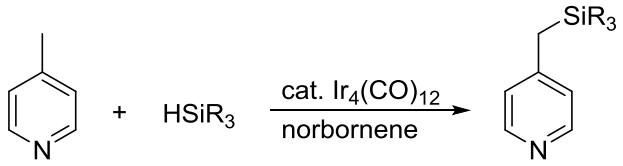
entry	catalyst	yield of **2a** (%)	remained **1a** (%)
1[b]	$Ir_4(CO)_{12}$	26	40
2	$Ir_4(CO)_{12}$	85 (79)[c]	10
3[d]	$Ir_4(CO)_{12}$	18	82
4[e]	$Ir_4(CO)_{12}$	82[f]	6
5[g]	$Ir_4(CO)_{12}$	71[h]	5
6[i]	$[Ir(OMe)(cod)]_2$	0	88
7[i]	$[Ir(OMe)(cod)]_2$/2Me_4phen[j]	0	78
8[i]	$[IrCl(cod)]_2$	0	81
9[i]	$[IrCl(cod)]_2$/2$NaBF_4$	0	81
10[k]	$Ir(acac)(CO)_2$	74[l]	3
11[i]	$[Ir(OMe)(cod)]_2$/CO (1 atm)	59	24
12	$Rh_4(CO)_{12}$	44	48
13[k]	$RhCl(PPh_3)_3$	43	46
14[m]	$Ru_3(CO)_{12}$	0	92

[a]Reaction conditions: **1a** (1 mmol), $HSiEt_3$ (2 mmol), catalyst (0.025 mmol), and norbornene (2 mmol) in toluene (1 mL) at 80 ºC for 20 h under N_2. Yields of **2a** and the remaining **1a** were determined from ^{1}H NMR spectra with 1,3-dihydro-2-benzofuran as an internal standard. [b]In the absence of norbornene. [c]The number in parenthesis is the isolated yield of **2a**. [d]*tert*-Butylethylene (2 mmol). [e]At 100 ºC. [f]4-[Bis(triethylsilyl)methyl]pyridine (**2a'**) was detected in 4% yield. [g]$HSiEt_3$ (4 mmol). [h]**2a'** was produced in 10% yield. [i]Catalyst (0.05 mmol). [j]Me_4phen: 3,4,7,8-tetramethylphenanthroline. [k]Catalyst (0.1 mmol). [l]**2a'** was produced in 15% yield. [m]Catalyst (0.033 mmol).

On the other hand, *tert*-butylethylene had no effect on the present C-H silylation of **1a** (entry 3). Attempts to achieve the complete consumption of **1a**, such as increasing the reaction temperature to 100 ºC and increasing the amount of $HSiEt_3$ to 4 mmol, resulted in the further C-H silylation of **2a** to produce 4-[bis(triethylsilyl)methyl]pyridine (**2a'**, entries 4 and 5). In addition, some other iridium-containing complexes, including $[Ir(OMe)(cod)]_2$, $[Ir(OMe)(cod)]_2$/2Me4phen, $[IrCl(cod)]_2$, and $[IrCl(cod)]_2$/2NaBF4, showed no catalytic activity (entries 6-9), but the use of $Ir(acac)(CO)_2$ resulting in the formation of **2a** in 74% (entry 10). Interestingly, the reaction catalyzed by $[Ir(OMe)(cod)]_2$ proceeded under 1 atmosphere of CO (entry 11). These results indicate that CO is crucial as a ligand for the present iridium-catalyzed reaction to proceed. Among complexes other than iridium that were examined, $Rh_4(CO)_{12}$ and $RhCl(PPh_3)_3$ also catalyzed reaction to give **2a** in moderate yields (entries 12 and 13). No reaction occurred when $Ru_3(CO)_{12}$ was used as a catalyst (entry 14).

The results for the reaction of **1a** with a series of hydrosilanes are summarized in Table 2. Tributylsilane also reacted to give **3a** in 65% (entry 2). On the other hand, triisopropylsilane, triphenylsilane, trimethoxysilane, and dimethyl(trimethylsiloxy)silane failed to function as silylation reagents (entries 3-6).

Table 2. Screening of Hydrosilanes[a]



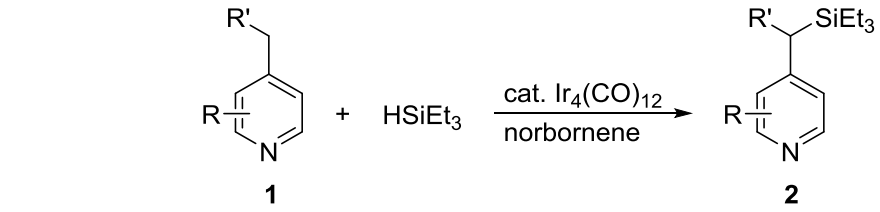
1a **2a-3a**

entry	hydrosilane	C-H silylationproduct	yield (%)[b]	remained **1a** (%)
1	$HSiEt_3$	**2a**	85 (79)	10
2	$HSiBu_3$	**3a**	65 (65)	22
3	HSi^iPr_3	-	0	94
4	$HSiPh_3$	-	0	86
5	$HSi(OEt)_3$	-	0	98
6	$HSi(OSiMe_3)Me_2$	-	0	78

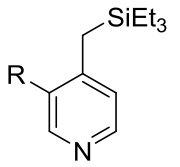
[a]Reaction conditions: **1a** (1 mmol), hydrosilane (2 mmol), $Ir_4(CO)_{12}$ (0.025 mmol), norbornene (2 mmol), in toluene (1 mL) at 80 ºC for 20 h under N_2. The yield of the remaining **1a** was determined from gas chromatogram with tridecane as an internal standard. The yield of the silylation product was determined from ^{1}H NMR spectra with 1,3-dihydro-2-benzofuran as an internal standard. [b]The number in parenthesis denotes the isolated yield.

To evaluate the scope of this catalytic reaction, the optimized reaction conditions were examined for a range of 4-alkylpyridines **1b-1o** (Table 3). The C-H silylation of 3,4-dimethylpyridine (**1b**) occurred regioselectively on the methyl group located at the 4-position to afford **2b** in 86% yield. Other alkyl and aryl groups at the 3-position also did not significantly affect product yields (**2c-2f**). Functional groups such as dimethylamino (**2g**), methoxy (**2h**), and chloro (**2i**) groups were compatible with the reaction, but the reaction of 3-bromopyridine (**1j**) afforded a mixture of **2j** and the reduction product **2a** in 61% and 9% yields, respectively. The more sterically hindered 3,4,5-trimethylpyridine (**1k**) was silylated to produce **2k** in 30% yield under the standard reaction conditions, but the product yield was improved to 50% by increasing the reaction temperature to 100 ºC.

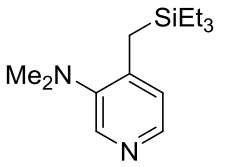
Table 3. Scope of Substrates[a]



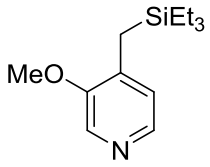
1 **2**



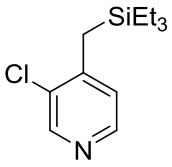
R = H (**2a**), 79% cyclo-C_5H_9 (**2d**), 84%
Me (**2b**), 86% Ph (**2e**), 74%[b]
C_4H_9 (**2c**), 76% 2-naph (**2f**), 75%



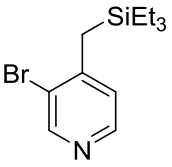
2g, 84%



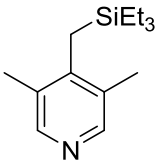
2h, 73%[b]



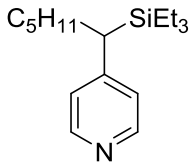
2i, 60%[b]



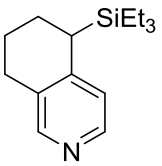
2j, 61%[b,c]



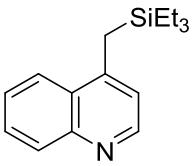
2k, 50%[b]



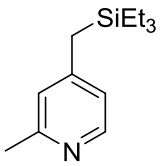
2l, 46%[b]



2m, 55%[d]



2n, 62%[d,e]

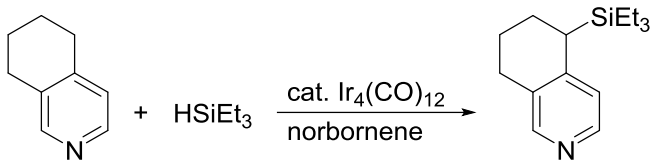


2o, 12%[d,e,f]

[a]Reaction conditions: **1** (1 mmol), $HSiEt_3$ (2 mmol), $Ir_4(CO)_{12}$ (0.025 mmol), and norbornene (2 mmol) in toluene (1 mL) at 80 ºC for 20 h under N_2. Isolated yields are given. [b]At 100 ºC. [c]**2a** was formed in 9% yield. [d]$HSiEt_3$ (4 mmol) and norbornene (4 mmol) for 48 h. [e]At 120 ºC. [f]Yield of **2o** was determined from ^1H NMR spectra with 1,3-dihydro-2-benzofuran as an internal standard.

Pyridines bearing a substituent other than a methyl group at the 4-position such as 4-hexylpyridine (**1l**) also underwent the benzylic C-H silylation to produce **2l** in 46% yield. The product **2m** was obtained by the reaction of 5,6,7,8-tetrahydroisoquinoline (**1m**) in 55% yield, after reoptimization of the reaction conditions (Table 4). However, the silylation of 4-isopropylpyridine did not proceed at all under the reaction conditions used.

Table 4. Reoptimization of the Reaction Conditions for **1m**[a]



1m **2m**

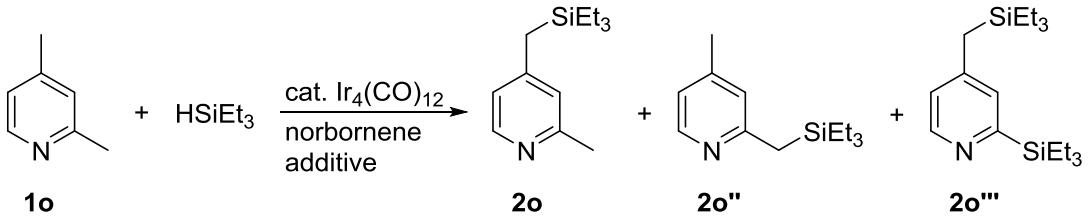
entry	$HSiEt_3$ (mmol)	norbornene (mmol)	temp.	yield of **2m** (%)[b]	remained **1m** (%)
1	2	2	80	34	55
2	2	2	80	42	48
3	4	2	80	50	25
4	4	4	80	61 (61)	23
5	4	4	120	39	36

[a]Reaction conditions: **1m** (1 mmol), $Ir_4(CO)_{12}$ (0.025 mmol), in toluene (1 mL) for 48 h under N_2. Yields of **2m** and the remaining **1m** were determined from ^1H NMR spectra with 1,3-dihydro-2-benzofuran as an internal standard. [b]The number in parenthesis denotes the isolated yield of **2m**.

Finally, I examined some 2-subustituted 4-methylpyridines. Although 4-methylquinoline (**1n**) reacted to afford **2n** in 62% at 120 ºC, the reaction of 2,4-dimethylpyridine (**1o**) resulted in a low yield of the product **2o** (12%) along with the recovery of **1o** in 65% yield. The substrate was completely recovered in the case of the reaction of 2,4,6-trimethylpyridine. Steric hindrance around the pyridine nitrogen in the substrate retarded the reaction, although it is located some distance from the reaction site. However, the author was pleased to find that some pyridine derivatives with no substituent at the 2-position, such as pyridine, 3-methylpyridine, 3,5-dimethylpyridine, and 3-methyl-5-phenylpyridine, participated in the reaction (entries 2-5 in Table 5). In these cases, the silylation product of the methyl group at the 2-position **2o**'' and the disilylation product at 2- and 4-positions **2o'''** were also formed, although in low yields. Furthermore, the regioselective $C(sp^2)$-H bond silylation of the added pyridine and 3-

methylpyridine at the 3-position was found to occur, with 3-triethylsilylpyridine and 3-methyl-5-triethylsilylpyridine, respectively, being formed (entries 2 and 3).[6] On the other hand, the yield of **2o** remained unchanged when 2,6-dimethylpyridine was added to the reaction mixture (entry 6). These results indicate that the nitrogen atom in the added pyridine ring plays an important role for the success of the reaction.

Table 5. Scope of Substrates[a]



1o **2o** **2o''** **2o'''**

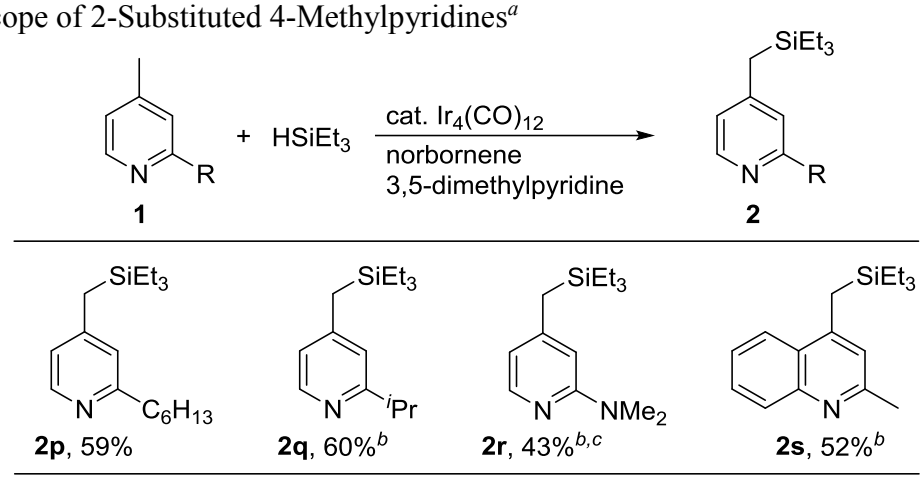
entry	additive	yields (%)			remained **1o** (%)
		2o	**2o''**	**2o'''**	
1	none	10	0	0	78
2[b]	pyridine	72	1	2	22
3[c]	3-methylpyridine	75	2	3	17
4	3,5-dimethylpyridine	73	2	3	14
5	3-methyl-5-phenylpyridine	75	1	2	19
6	2,6-dimethylpyridine	14	0	0	60
7	phenanthlorine	40	0	0	41
8	Me_4phen	15	1	0	73
9	5,5'-dimethyl-2,2'-dipyridine	20	0	0	61
10	Et_3N	23	0	0	53
11	DBU	0	0	0	94
12[d]	none	0	0	0	67
13[d]	3,5-dimethylpyridine	34	1	0	51

[a]Reaction conditions: **1o** (1 mmol), $HSiEt_3$ (2 mmol), $Ir_4(CO)_{12}$ (0.025 mmol), norbornene (2 mmol), and additive (0.2 mmol) in toluene (1 mL) at 100 ºC for 20 h under N_2. Yields of **2o** and the remaining **1o** were determined from ^{1}H NMR spectra with 1,3-dihydro-2-benzofuran as an internal standard. [b]3-Triethylsilylpyridine was detected in 22% yield. [c]3-Methyl-5-triethylsilylpyridine was detected in 27% yield. [d]$Ir(acac)(CO)_2$ (0.1 mmol) as a catalyst.

Some 2-substituted 4-methypyridine derivatives were next examined under the revised reaction conditions (Table 6). However, the reactivity of these derivatives was affected by the bulkiness of the substituent at the 2-position. 2-Hexyl-4-methylpyridine (**1p**) exhibited low reactivity to afford **2p** in 30% yield, along with the recovery of **1p** in 64% yield. Therefore, the reaction in the case of **1p** was carried out at 120 ºC, and **2p** was produced in 59% yield. 4-Methypyridine

substituted with an isopropyl group at the 2-position was also silylated at 160 ºC to furnish **2q** in 60% yield. The reaction conditions were also applicable to 2-dimethylamino-4-methylpyridine (**1r**) and 2,4-dimethylquinoline (**1s**) to afford **2r** and **2s** in 43% and 52% yields, respectively, and no silylated product of other methyl groups was detected. Nevertheless, 2,4,6-trimethylpyridine remained intact during the reaction.

Table 6. Scope of 2-Substituted 4-Methylpyridines[a]



[a]Reaction conditions: **1** (1 mmol), $HSiEt_3$ (4 mmol), $Ir_4(CO)_{12}$ (0.025 mmol), norbornene (4 mmol), and 3,5-dimethylpyridine (0.2 mmol) in toluene (1 mL) at 120 ºC for 48 h under N_2. Isolated yields are given. [b]At 160 ºC. [c]For 5 days.

To gain some additional insights into the reaction mechanism, deuterium labeling experiments using $DSiEt_3$ were carried out, and the results are shown in Scheme 2. The results are summarized as follows:

(1) whereas benzylic C-H bond cleavage occurred at the 2- and 4-positions, cleavage at the 3-position was not confirmed;

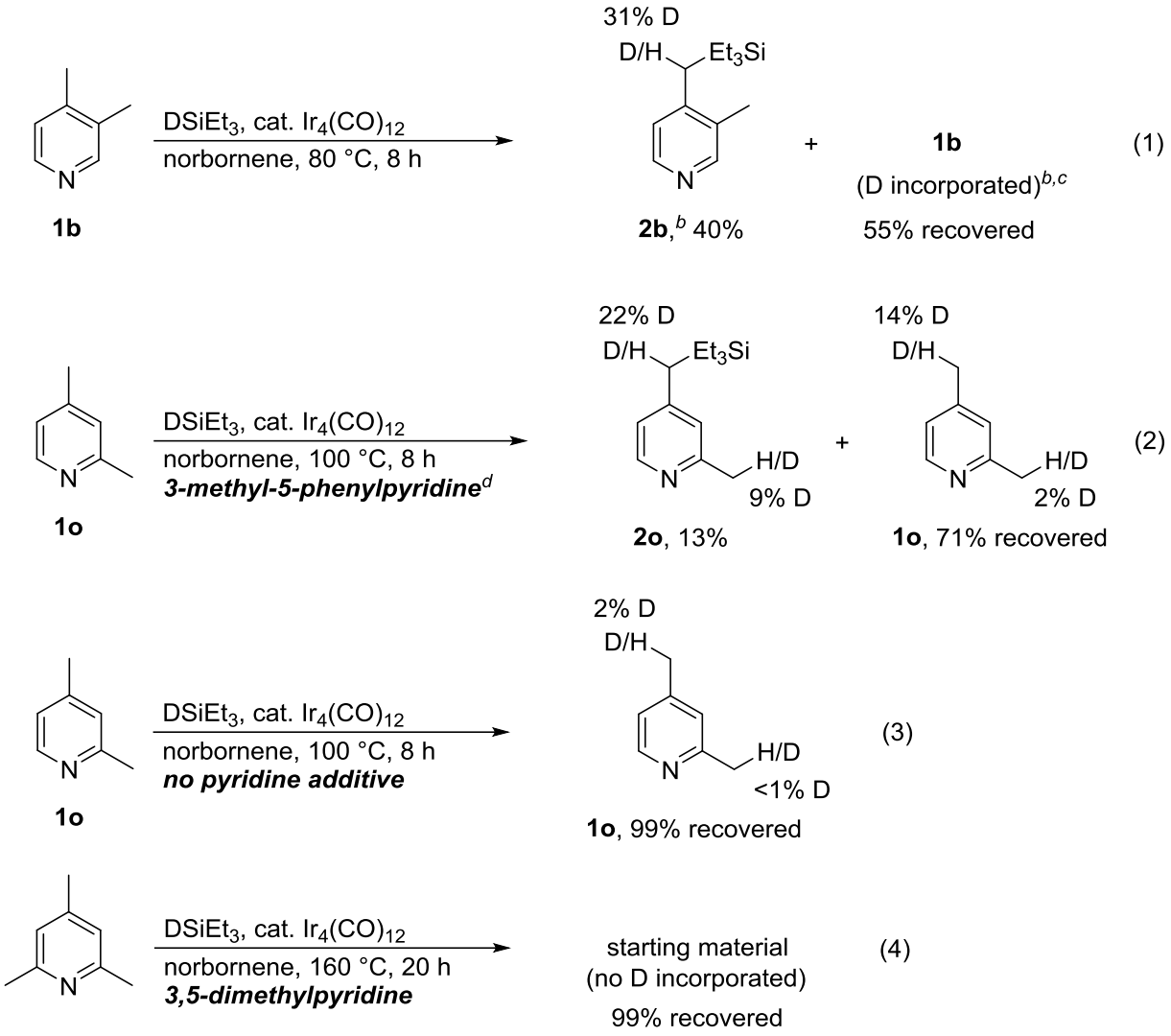
(2) cleavage of the benzylic C-H bond at the 4-position took place more frequently rather than that at the 2-position;

(3) The presence of pyridine clearly accelerated C-H bond cleavage;

(4) no C-H bond cleavage was observed in the reaction of 2,4,6-trimethylpyridine even in the presence of 3,5-dimethylpyridine.

This fact indicates that the pyridine nitrogen atom in the substrate also appears to play an important role in this catalytic C-H bond cleavage.

Scheme 2. Deuterium Labelling Experiments[a]

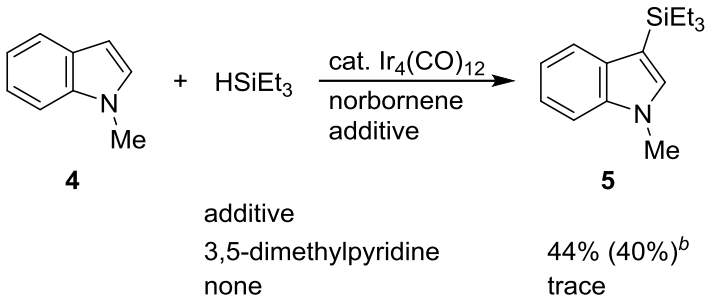


[a]Reaction conditions: **1** (1 mmol), $DSiEt_3$ (2 mmol), $Ir_4(CO)_{12}$ (0.025 mmol), norbornene (2 mmol), and additive (0.2 mmol) in toluene (1 mL) under N_2. Yields of **2** and the recovered **1**, and deuterium content were determined from ^1H and ^2H NMR spectra. 1,3-Dihydro-2-benzofuran was used as an internal standard to determine the yields. [b]Due to the overlap of two peaks assigned as the hydrogens at the 2- and 6-positions in the pyridine ring, the location where deuterium was incorporated could not be determined. [c]Due to the overlap of two peaks assigned as the methyl groups at the 3- and 4-positions, the location where deuterium was incorporated could not be determined. [d]Deuterium was also incorporated into the recovered 3-methyl-5-phenylpyridine.

The applicability of the present C-H bond silylation to other substrates was investigated. The C-H bond at the 3-position of *N*-methylindole (**4**) participated in the reaction to afford **5** in 44% yield (Scheme 3).[7] The presence of 3,5-dimethylpyridine was also crucial for the reaction to

proceed, based on the fact that only a trace amount of **5** was formed when the reaction was run in the absence of 3,5-dimethylpyridine.

Scheme 3. Reaction of *N*-Methylindole **4**[a]



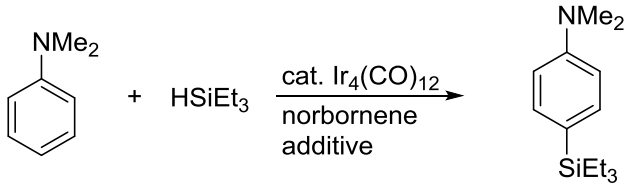
4 **5**

additive	
3,5-dimethylpyridine	44% (40%)[b]
none	trace

[a]Reaction conditions: **4** (0.5 mmol), $HSiEt_3$ (1 mmol), $Ir_4(CO)_{12}$ (0.0125 mmol), norbornene (1 mmol), and 3,5-dimethylpyridine (0.1 mmol) in toluene (0.5 mL) at 120 ºC for 20 h under N_2. NMR yields were determined from ^1H NMR spectra with 1,3-dihydro-2-benzofuran as an internal standard. [b]The number in parenthesis denotes the isolated yield of **5**.

N,*N*-Dimethylaniline (**6**) could be also used as a substrate under the reaction conditions, with the *para*-silylated compound **7** being produced in 11% yield (Scheme 4).[7b,c,e] In light of previous studies on the mechanism of these reactions, it appears that the present iridium-catalyzed reaction involves the formation of an electrophilic silicon species as an intermediate. [8]

Scheme 4. Reaction of *N,N*-Dimethylaniline **6**[a]



6 **7**

11% (10%)[b]

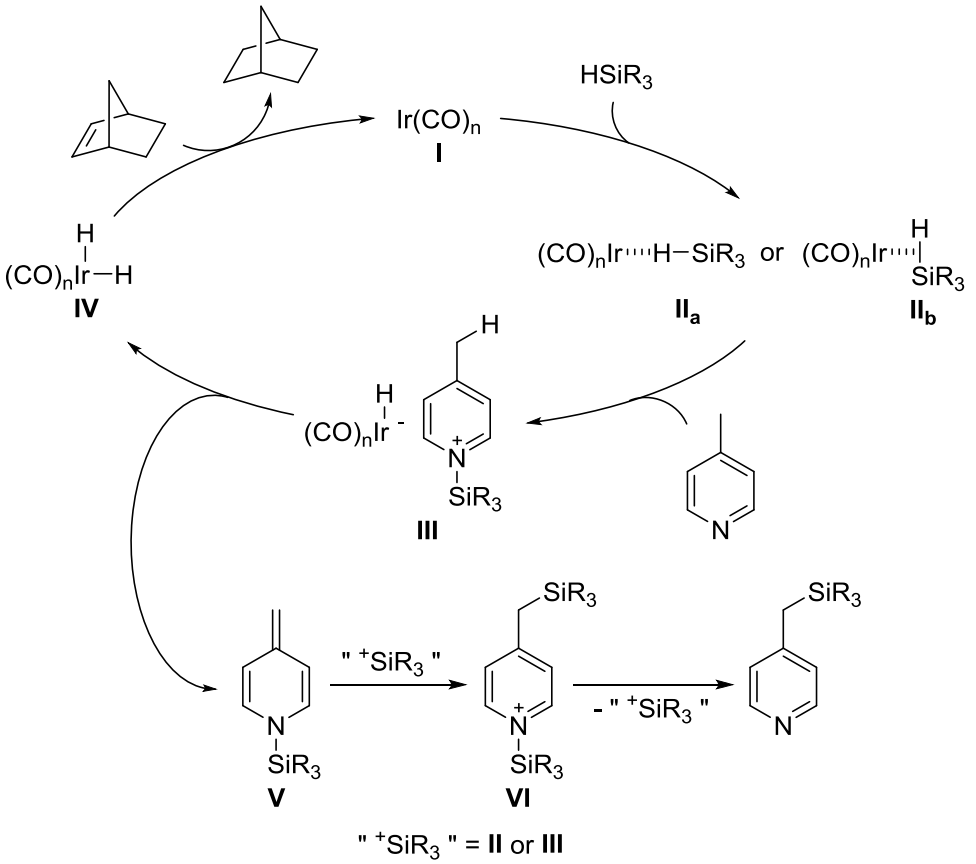
[a]Reaction conditions: **6** (0.5 mmol), $HSiEt_3$ (2 mmol), $Ir_4(CO)_{12}$ (0.0125 mmol), norbornene (0.5 mmol), and 3,5-dimethylpyridine (0.1 mmol) in toluene (0.5 mL) at 160 ºC for 3 days under N_2. NMR yields were determined from ^1H NMR spectra with 1,3-dihydro-2-benzofuran as an internal standard. [b]The number in parenthesis denotes the isolated yield of **7**.

A proposed mechanism for the regioselective benzylic C(sp^3)-H bond silylation of 4-alkylpyridines is depicted in Scheme 5, although details are unclear at the present stage. An iridium complex reacts with a hydrosilane to form an electrophilic silicon species **II**,[9] which is an η^1-silane complex **II$_a$**, or a σ-silane complex **II$_b$**, as a plausible key intermediate.[10] *N*-Silylpyridinium iridate **III** is formed by the reaction of **II** with the substrate pyridine, through an outer-sphere silicon transfer pathway.[8] The author concludes that the π-acidic nature of CO as a ligand might promote the abstraction of a hydride from the hydrosilane to form **III**,[11] or, stabilize the anionic character of the hydridoiridate species in **III**. Proton abstraction at the benzylic position of the *N*-silylpyridinium species by a hydridoiridate species then takes place to afford a dihydridoiridium complex **IV** and the silylenamine **V**. Therefore, the reaction can be regarded as a new type of dehydrogenative silylation of pyridines. The silyl group on the pyridine nitrogen hampers the abstraction of the benzylic proton at the 2-position because of steric factors.[12] **IV** reacts with norbornene to give norbornane, along with the regeneration of **I**. The enamine **V** undergoes silylation with either the electrophilic silicon species **II** or the silylpyridinium species **III** to furnish **VI**,[6c,13] and the subsequent elimination of the silyl group from the nitrogen in **VI** produces the product. Although the reason why the reaction is accelerated by the addition of 3,5-dimethylpyridine is quite unclear, it might participate in the reaction as a ligand or, possibly, as the porter of the silyl group to 2,4-dimethylpyridine after the formation of the *N*-silyl-3,5-dimethylpyridinium species.[14] The latter possibility might explain the reason why 3,5-dimethylpyridine is required in the C-H silylation of *N*-methylindoles. However, we currently have no direct evidence for shuffling of the silyl group between these pyridine derivatives.

1.3 Conclusion

The author has demonstrated the iridium-catalyzed regioselective C(sp^3)-H bond silylation of 4-alkylpyridines with hydrosilanes. The reaction proceeded in the presence of a catalytic amount of $Ir_4(CO)_{12}$ or $Ir(acac)(CO)_2$, which possess CO as a ligand, or $[Ir(OMe)(cod)]_2$ under 1 atmosphere of CO. The low product yields in the reaction of 2-substituted 4-methylpyridines under the optimized reaction conditions could be markedly improved by adding other pyridine derivatives, such as 3,5-dimethylpyridine as additives.

Scheme 5. A Proposed Reaction Mechanism



1.4 Experimental Section

General Information.

^{1}H, ^{2}H, and ^{13}C NMR spectra were recorded on 400, 61, and 100 MHz spectrometers, respectively, using $CDCl_3$ and C_6D_6 as solvents. Data are recorded as follows: chemical shifts in ppm (δ), multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, c = complex), coupling constant (Hz), and integration. Infrared spectra (IR) were recorded using ATR. Absorption data are reported in reciprocal centimeters with the following relative intensities: s (strong), m (medium), or w (weak). Mass spectra were obtained using a spectrometer with a quadrupole mass analyzer at 70 eV. High-resolution mass spectra (HRMS) were obtained using a spectrometer with a double-focusing mass analyzer. Analytical gas chromatography (GC) was carried out on a chromatograph equipped with a flame ionization detector. Melting points were determined on a capillary point apparatus equipped with a digital thermometer and are uncorrected.

Materials.

Toluene was purified by passage through activated alumina under a positive pressure of N_2. Norbornene and $DSiEt_3$ were purchased and were used as received. Other organic compounds, except **1c-h**, **1k**, **1l**, and **1p-r**, were purchased and distilled over CaH_2 before use. Compounds **1c-h**, **1k**, and **1p** were prepared as described below. Compounds **1l**,[15] **1q**,[16] and **1r**[17] were prepared following procedure described in the literature. All metal complexes were purchased and used without further purification.

Typical Procedure for the $Ir_4(CO)_{12}$-Catalyzed C-H Silylation of Pyridines with Hydrosilanes.

A 25 mL Schlenk tube was flame-dried and purged with N_2. After cooling to room temperature, $Ir_4(CO)_{12}$ (27.6 mg, 0.025 mmol), toluene (1 mL), hydrosilane (2 mmol), **1** (1 mmol), and norbornene (188 mg, 2 mmol) were placed in the Schlenk tube. The reaction mixture was stirred at 80 °C for 20 h. After cooling to room temperature, the volatile were removed *in vacuo.* The product was isolated by flash column chromatography on silica-gel.

Typical Procedure for the Deuterium Labelling Experiments using $DSiEt_3$.

The reaction was carried out in the same manner as described above, except that $DSiEt_3$ (234 mg, 2 mmol) was added to the reaction mixture, in place of $HSiEt_3$. After the reaction, the reaction mixture was cooled to room temperature and concentrated under reduced pressure (150 mmHg) at 40 °C. The yields of the silylated product and the remaining unreacted starting pyridine were determined from ^1H NMR spectroscopy with 1,3-dihydro-2-benzofuran as the internal standard. They were then separated by flash column chromatography on silica-gel. However, in consideration of the high volatility of the compounds, the complete removal of eluent under reduced pressure was not made. The deuterium content of the compounds was determined from ^1H and ^2H NMR spectroscopy.

The Deuterium Labelling Experiment of 1b with $DSiEt_3$.

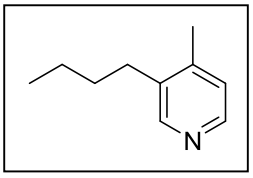
The reaction was carried out at 80 °C for 8 h. After cooling and evaporation of the reaction mixture, **1b** and **2b** were separated by flash column chromatography on silica-gel (**1b**: R_f = 0.20 in pentane/Et_2O = 1/1, **2b**: R_f = 0.26 in pentane/Et_2O = 1/1).

Labelling Experiment of 1o with $DSiEt_3$ in the Presence of 3-Methyl-5-phenylpyridine. The reaction was carried out at 100 °C for 8 h. After cooling and evaporation of the reaction mixture, **1o** and **2o** were separated by flash column chromatography on silica-gel (**1o**: R_f = 0.14 in pentane/Et_2O = 1/1, **2o**: R_f = 0.21 in pentane/Et_2O = 1/1). However, **2o** was obtained as a mixture with 3-methyl-5-phenylpyridine.

The Deuterium Labelling Experiment of 2,4,6-Trimethylpyridine with $DSiEt_3$ in the Presence of 3,5-Dimethylpyridine.

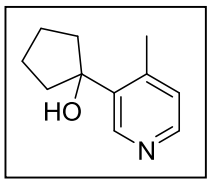
The reaction was carried out at 160 °C for 20 h. After cooling and evaporation of the reaction mixture, no production of the silylated product was confirmed from ^1H NMR spectroscopy. Therefore, the yield and deuterium content of 2,4,6-trimethylpyridine were determined from ^1H and ^2H NMR spectroscopy of the unpurified reaction mixture.

3-Butyl-4-methylpyridine (1c).[18]



The procedure described in the patent[19] was modified by using 3-bromo-4-methylpyridine (3.95 g, 23.0 mmol) and $ZnBu_2$,[20] in place of methyl 5-bromonicotinate and $ZnEt_2$, respectively, to produce **1c**, which was isolated by flash column chromatography on silica-gel (R_f = 0.20 in hexane/EtOAc = 3/1) and subsequent distillation under reduced pressure (74 °C/8.3 mmHg) in 16% yield (570 mg, 3.68 mmol) as a colorless oil. ^1H NMR ($CDCl_3$) δ: 0.94 (t, *J* = 7.5 Hz, 3H), 1.36-1.40 (sextet, *J* = 7.5 Hz, 2H), 1.49-1.57 (quintet, *J* = 7.5 Hz, 2H), 2.39 (s, 3H), 2.64 (t, *J* = 7.5 Hz, 2H), 7.26 (d, *J* = 5.0 Hz, 1H), 8.44 (d, *J* = 5.0 Hz, 1H), 8.47 (s, 1H). ^{13}C NMR ($CDCl_3$) δ: 13.9, 19.2, 22.7, 30.4, 32.0, 126.8, 139.1, 145.8, 148.2, 150.5.

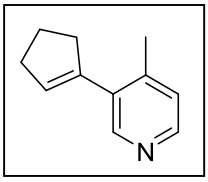
1-(4-Methylpyridin-3-yl)cyclopentan-1-ol (pre-1d-i).



The procedure reported by Vacher[21] was modified by using ethyl 4-methylnicotinate[22] (6.61 g, 40.0 mmol) in place of ethyl 5-bromonicotinate to produce **pre-1d-i**, which was isolated by flash column chromatography on NH_2 modified silica-gel (R_f = 0.23 in hexane/EtOAc = 1/1) in 54% yield (3.86 g, 21.6 mmol) as a white solid. Mp = 88.7-89.2 ºC. ^1H NMR ($CDCl_3$) δ: 1.78-1.83 (m, 2H), 1.95-1.96 (m, 2H), 2.07-2.21 (m, 4H), 2.58 (s, 3H), 7.09 (d, *J* = 4.8 Hz, 1H), 8.35 (d, *J* = 4.8 Hz, 1H), 8.58 (s, 1H). ^{13}C NMR ($CDCl_3$) δ: 21.4, 23.5, 39.6, 82.2, 127.0, 140.0, 146.1, 147.5, 148.0. IR

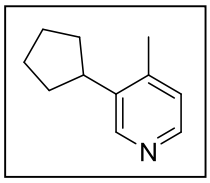
(ATR): 3131 w, 2952 w, 2871 w, 2806 w. MS, *m/z* (EI, relative intensity, %): 159 (90), 158 (100), 148 (23), 144 (39), 135 (10), 120 (93). Anal. Calcd for $C_{16}H_{13}N$: C, 74.54; H, 8.53; N, 7.90. Found: C, 74.29; H, 8.53; N, 7.86.

3-(Cyclopent-1-en-1-yl)-4-methylpyridine (pre-1d-ii).



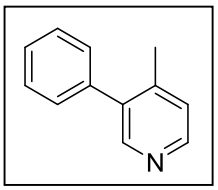
The procedure reported by Vacher[21] was modified by using **pre-1d-i** (3.52 g, 20.0 mmol) in place of 1-(5-bromo-pyridin-3-yl)cyclopentanol to produce **pre-1d-ii**, which was isolated by distillation under reduced pressure (74 °C/7.5 mmHg) in 63% yield (2.01 g, 12.6 mmol) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 1.99-2.06 (quintet, J = 7.4 Hz, 2H), 2.35 (s, 3H), 2.52-2.58 (m, 2H), 2.66-2.71 (m, 2H), 5.86-5.88 (m, 1H), 7.07 (d, J = 4.8 Hz, 1H), 8.31 (d, J = 4.8 Hz, 1H), 8.39 (s, 1H). ^{13}C NMR ($CDCl_3$) δ: 20.6, 23.6, 33.5, 36.2, 125.2, 131.5, 134.0, 140.0, 144.3, 147.5, 148.6. IR (ATR): 3044 w, 3020 w, 2952 w, 2845 w. MS, *m/z* (EI, relative intensity, %): 159 (M^+, 98), 158 (100), 144 (69), 143 (21), 131 (29), 130 (23), 117 (18), 115 (11), 77 (15). HRMS Calcd for $C_{11}H_{13}NSi$ (M^+): 159.1048. Found: 159.1047.

3-Cyclopentyl-4-methylpyridine (1d).



The procedure described in the patent[23] was modified by using **pre-1d-ii** (1.75 g, 11.0 mmol) in place of 5-cyclopentylpyridine-2-carboxylic acid to produce **1d**, which was isolated by distillation under reduced pressure (65 °C/8.2 mmHg) in 89% yield (1.58, 9.79 g) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 1.61-1.74 (m, 4H), 1.83-1.85 (m, 2H), 2.01-2.08 (m, 2H), 2.33 (s, 3H), 3.11-3.19 (m, 1H), 7.01 (d, J = 4.8 Hz, 1H), 8.27 (d, J = 4.8 Hz, 1H), 8.44 (s, 1H). ^{13}C NMR ($CDCl_3$) δ: 19.2, 25.5, 33.1, 39.9, 124.9, 139.8, 144.9, 146.8, 147.2. IR (ATR): 2952 w, 2868 w. MS, *m/z* (EI, relative intensity, %): 161 (M^+, 72), 160 (22), 146 (17), 133 (37), 132 (100), 120 (52), 119 (74), 118. (47), 117 (45), 106 (20), 91 (16), 77 (12). Anal. Calcd for $C_{11}H_{15}N$: C, 81.94; H, 9.38; N, 8.69. Found: C, 81.87; H, 9.34; N, 8.67.

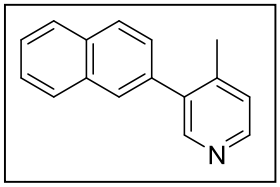
4-Methyl-3-phenylpyridine (1e).[24]



The procedure reported by Horenstein[25] was modified by using 3-bromo-4-methylpyridine (3.62 g, 21.1 mmol) in place of 3,5-dibromopyridine to produce **1e**, which was isolated by column chromatography on silica-gel (R_f

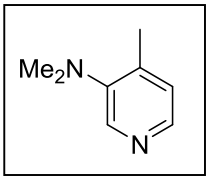
= 0.08 in hexane/EtOAc = 6/1) and subsequent distillation under reduced pressure (100 °C/3.0 mmHg) in 69% (2.23 g, 14.6 g) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 2.29 (s, 3H), 7.19 (d, *J* = 5.0 Hz, 1H), 7.31-7.33 (m, 2H), 7.38-7.48 (m, 3H), 8.44-8.45 (m, 2H). ^{13}C NMR ($CDCl_3$) δ: 19.8, 125.2 127.6, 128.4, 129.3, 137.7, 137.9, 144.5, 148.3, 150.0.

4-Methyl-3-(naphthalen-2-yl)pyridine (1f).[26]



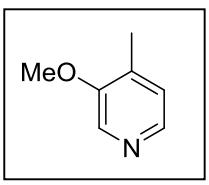
The procedure reported by Horenstein[25] was modified by using 3-bromo-4-methylpyridine (3.62 g, 21.1 mmol) in place of 3,5-dibromopyridine to produce **1f,** which was isolated by column chromatography on silica gel (R_f = 0.19 in hexane/EtOAc = 3/1) and subsequent recrystallization from Hexane/EtOAc in 79% yield (3.28 g, 16.7 mmol) as a white solid. Mp = 60.9-61.4 ºC. ^{1}H NMR ($CDCl_3$) δ: 2.34 (s, 3H), 7.23 (d, *J* = 5.0 Hz, 1H), 7.45 (d, *J* = 8.2 Hz, 1H), 7.53-7.55 (m, 2H), 7.79 (s, 1H), 7.89-7.92 (m, 3H), 8.49 (d, *J* = 5.0 Hz, 1H), 8.53 (s, 1H). ^{13}C NMR ($CDCl_3$) δ: 20.0, 125.3, 126.4, 126.6, 127.4, 127.8, 128.09, 128.12, 128.3, 132.7, 133.3, 135.5, 137.8, 144.8, 148.5, 150.2.

***N*,*N*,4-Trimethylpyridin-3-amine (1g)**.



The procedure reported by Aron[27] was modified by using 4-methylpyridin-3-amine (5.00 g, 46.2 mmol) in place of pyridin-3-amine to produce **1g**, which was isolated by distillation under reduced pressure (55 °C/3.0 mmHg) in 96% yield (4.79 g, 44.4 mmol) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 2.31 (s, 3H), 2.76 (s, 6H), 7.04 (d, *J* = 4.6 Hz, 1H), 8.15 (d, *J* = 4.6 Hz, 1H), 8.26 (s, 1H). ^{13}C NMR ($CDCl_3$) δ: 18.1, 43.9, 125.8, 140.6, 140.8, 143.8, 148.6. IR (ATR): 3038 w, 2980 w, 2943 w, 2865 w, 2832 w, 2784 w. MS, *m/z* (EI, relative intensity, %): 136 (M^+, 100), 135 (98), 121 (27), 119 (24), 105 (18), 94 (15), 93 (14), 92 (26), 65 (19), 53 (10). HRMS Calcd for $C_8H_{12}N_2$ (M^+): 137.1079. Found: 137.1077.

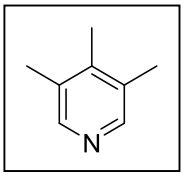
3-Methoxy-4-methylpyridine (1h).[28]



The procedure reported by Buchwald[29] was modified by using 3-bromo-4-methylpyridine (2.58 g, 15.0 mmol) in place of 2-chloro-5-iodopyridine to produce **1h**, which was isolated by column chromatography on silica gel (R_f = 0.20 in pentane/Et_2O = 2/1) and subsequent distillation under reduced

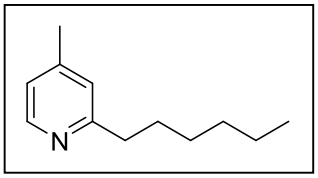
pressure (42 °C/8.3 mmHg) in 18% yield (334 mg, 2.85 mmol) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 2.23 (s, 3H), 3.92 (s, 3H), 7.06 (d, *J* = 4.6 Hz, 1H), 8.12 (d, *J* = 4.6 Hz, 1H), 8.17 (s, 1H). ^{13}C NMR ($CDCl_3$) δ: 15.7, 55.9, 125.4, 132.4, 135.5, 142.5, 154.4.

3,4,5-Trimethylpyridine (1k).[30]



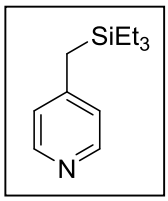
The procedure reported by Naveschuk[31] was modified by using 3,5-dibromo-4-methylpyridine (5.00 g, 20.0 mmol) in place of ethyl 3,5-dibromoisonicotinate to produce **1k**, which was isolated by column chromatography on silica gel (R_f = 0.29 in Et_2O) and subsequent sublimation (38 °C/6.8 mmHg) in 6% (144 mg, 1.2 mmol) as a white solid. Mp = 33.1-33.6 °C. ^{1}H NMR ($CDCl_3$) δ: 2.18 (s, 3H), 2.25 (s, 6H), 8.19 (s, 2H). ^{13}C NMR ($CDCl_3$) δ: 15.0, 16.9, 131.4, 144.1, 148.2.

2-Hexyl-4-methylpyridine (1p).[32]



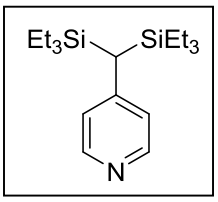
The procedure with 2-bromo-4-methylpyridine (3.92 g, 22.8 mmol) as a starting material, reported by Delort,[33] was modified by using 3.0 M hexylmagnesium bromide (11.5 mL, 34.8 mmol) in place of pentylmagnesium bromide to produce **1p**, which was isolated by column chromatography on silica gel (R_f = 0.23 in hexane/EtOAc = 8/1) and subsequent distillation under reduced pressure (72 °C/9.5 mmHg) in 26% yield (1.09 g, 9.00 mmol) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.88 (t, *J* = 7.1 Hz, 3H), 1.28-1.37 (m, 6H), 1.68-1.71 (m, 2H), 2.31 (s, 3H), 2.73 (t, *J* = 7.8 Hz, 2H), 6.91 (d, *J* = 5.0 Hz, 1H), 6.96 (s, 1H), 8.36 (d, *J* = 5.0 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 14.1, 21.1, 22.6, 29.2, 30.0, 31.8, 38.2, 122.03, 123.7, 147.7, 148.6, 162.2.

4-[(Triethylsilyl)methyl]pyridine (2a).



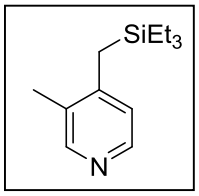
2a was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.17 in hexane) in 79% yield as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 0.52 (q, *J* = 7.9 Hz, 6H), 0.93 (t, *J* = 7.9 Hz, 9H), 2.11 (s, 2H), 6.94 (dd, *J* = 4.5, 1.7 Hz, 2H), 8.38 (dd, *J* = 4.5, 1.7 Hz, 2H). ^{13}C NMR ($CDCl_3$) δ: 2.9, 7.3, 22.2, 123.7, 149.4, 150.7. IR (ATR): 2952 w, 2909 w, 2875 w, MS, *m/z* (EI, relative intensity, %): 207 (M^+, 38), 150 (11), 122 (24), 120 (11), 115 (30), 87 (100), 59 (32). HRMS Calcd for $C_{12}H_{21}NSi$ (M^+): 207.1443. Found: 207.1444.

4-[Bis(triethylsilyl)methyl]pyridine (2a').



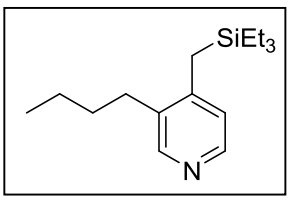
2a' was produced by the present $Ir_4(CO)_{12}$-catalyzed reaction of **2a** (207 mg, 1.00 mmol) with $HSiEt_3$ (640 μL, 4.00 mmol) in the presence of norbornene (376 mg, 4.00 mmol) at 160 °C for 48 h. The product was isolated by flash column chromatography on silica-gel (R_f = 0.11 in hexane/EtOAc = 5/1) in 14% yield (44.0 mg) as a pale yellow oil. ^{1}H NMR ($CDCl_3$) δ: 0.58 (q, *J* = 7.9 Hz, 12H), 0.90 (t, *J* = 7.9 Hz, 18H), 1.82 (s, 1H), 6.91 (d, *J* = 6.0 Hz, 2H), 8.33 (d, *J* = 6.0 Hz, 2H). ^{13}C NMR ($CDCl_3$) δ: 4.8, 7.9, 23.4, 124.8, 149.1, 153.2. IR (ATR): 2952 w, 2910 w, 2876 w. MS, *m/z* (EI, relative intensity, %): 293 (18), 292 (31), 266 (12), 265 (100), 264 (58), 237 (42), 236 (38), 220 (53), 208 (14), 115 (21), 87 (60), 59 (48). HRMS Calcd for $C_{18}H_{35}NSi_2$ (M^+): 321.2308. Found: 321.2303.

3-Methyl-4-[(triethylsilyl)methyl]pyridine (2b).



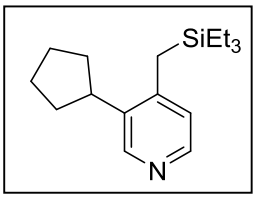
2b was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.10 in hexane) in 86% yield as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 0.54 (q, *J* = 8.0 Hz, 6H), 0.91 (t, *J* = 8.0 Hz, 9H), 2.11 (s, 2H), 2.22 (s, 3H), 6.88 (d, *J* = 5.0 Hz, 1H), 8.21 (d, *J* = 5.0 Hz, 1H), 8.26 (s, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.5, 7.3, 17.0, 19.1, 123.6, 130.4, 146.9, 149.2, 150.6. IR (ATR): 2952w, 2909 w, 2875 w. MS, *m/z* (EI, relative intensity, %): 221 (M^+, 38), 136 (12), 115 (28), 87 (100), 59 (31). HRMS Calcd for $C_{13}H_{23}NSi$ (M^+): 221.1600. Found: 221.1595.

3-Butyl-4-[(triethylsilyl)methyl]pyridine (2c).



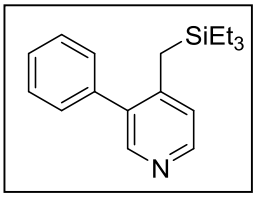
2c was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.11 in hexane/EtOAc = 30/1) in 76% yield as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.54 (q, *J* = 7.8 Hz, 6H), 0.91-0.95 (m, 12H), 1.39-1.42 (sixtet, *J* = 7.4 Hz, 2H), 1.52-1.60 (quintet, J = 7.4 Hz, 2H), 2.13 (s, 2H), 2.55 (t, *J* = 7.4 Hz, 2H), 6.87 (d, *J* = 5.0 Hz, 1H), 8.20 (d, *J* = 5.0 Hz, 1H), 8.26 (s, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.5, 7.3, 14.1, 18.6, 22.8, 30.4, 32.7, 124.0, 135.0, 146.8, 148.4, 150.2. IR (ATR): 2953 w, 2933 w, 2912 w, 2874 w. MS, *m/z* (EI, relative intensity, %): 248 (27), 234 (18), 221 (100), 134 (11), 115 (57), 106 (19), 87 (90), 59 (34). HRMS Calcd for $C_{16}H_{30}NSi$ (M^++1): 264.2148. Found: 264.2148.

3-Cyclopentyl-4-[(triethylsilyl)methyl]pyridine (2d).



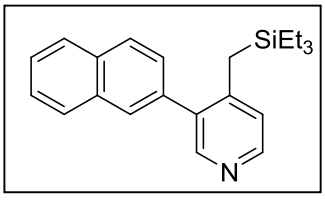
2d was obtained by flash column chromatography on silica-gel (R_f = 0.16 in hexane/EtOAc = 5/1) in 84% yield as a pale yellow oil. Analytically pure sample was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.20 in hexane/EtOAc = 30/1). ^{1}H NMR ($CDCl_3$) δ: 0.54 (q, *J* = 8.0 Hz, 6H), 0.91 (t, *J* = 8.0 Hz, 9H), 1.63-1.69 (m, 4H), 1.84-1.88 (m, 2H), 2.00-2.06 (m, 2H), 2.17 (s, 2H), 3.04-3.12 (quintet, *J* = 8.4 Hz, 1H), 6.85 (d, *J* = 4.6 Hz, 1H), 8.17 (d, *J* = 4.6 Hz, 1H), 8.38 (s, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.5, 7.4, 19.0, 25.9, 34.3, 39.8, 123.9, 138.7, 146.2, 147.9, 148.3. IR (ATR): 2952 w, 2909 w, 2873 w. MS, *m/z* (EI, relative intensity, %): 275 (M^+, 11), 274 (18), 247 (23), 246 (25), 235 (19), 234 (100), 232 (26), 132 (13), 121 (11), 1115 (44), 87 (77), 59 (36). HRMS Calcd for $C_{17}H_{29}NSi$ (M^+): 275.2069. Found: 275.2066.

3-Phenyl-4-[(triethylsilyl)methyl]pyridine (2e).



2e was obtained by flash column chromatography on silica-gel (R_f = 0.23 in hexane/EtOAc = 10/1) in 74% yield as a colorless oil. Analytically pure sample was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.26 in hexane). ^{1}H NMR ($CDCl_3$) δ: 0.33 (q, *J* = 7.8 Hz, 6H), 0.70 (t, *J* = 7.8 Hz, 9H), 2.26 (s, 2H), 7.02 (d, *J* = 5.0 Hz, 1H), 7.33-7.38 (m, 3H), 7.44 (t, *J* = 7.6 Hz, 2H), 8.33-8.35 (m, 2H). ^{13}C NMR ($CDCl_3$) δ: 3.4, 7.1, 18.8, 124.2, 127.5, 128.6, 129.8, 136.7, 138.6, 147.9, 148.4, 150.5. IR (ATR): 2952 w, 2908 w, 2874 w. MS, *m/z* (EI, relative intensity, %): 283 (M^+, 26), 282 (89), 254 (12), 115 (38), 87 (100), 59 (46). HRMS Calcd for $C_{18}H_{25}NSi$ (M^+): 283.1756. Found: 283.1746.

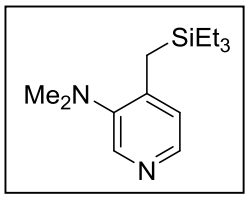
3-(Naphthalen-2-yl)-4-[(triethylsilyl)methyl]pyridine (2f).



2f was obtained by flash column chromatography on silica-gel (R_f = 0.20 in hexane/EtOAc = 4/1) in 75% yield as a pale yellow oil. Analytically pure sample was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.09 in hexane/EtOAc = 30/1). ^{1}H NMR ($CDCl_3$) δ: 0.33 (q, *J* = 8.0 Hz, 6H), 0.67 (t, *J* = 8.0 Hz, 9H), 2.31 (s, 2H), 7.07 (d, *J* = 5.0 Hz, 1H), 7.47 (d, *J* = 8.2 Hz, 1H), 7.52-7.54 (m, 2H), 7.79 (s, 1H), 7.87-7.92 (m, 3H), 8.39 (d, *J* = 5.0 Hz, 1H), 8.43 (s, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.4, 7.1, 19.1, 124.2, 126.3, 126.5, 127.9, 128.7, 132.6, 133.5, 136.1, 136.7, 148.2, 148.6, 150.8. IR (ATR):

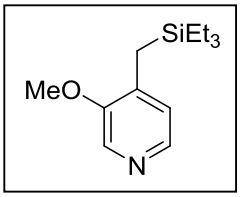
2952 w, 2908 w, 2874 w. MS, *m/z* (EI, relative intensity, %): 333 (M^+, 38), 332 (100), 304 (34), 219 (18), 218 (16), 217 (14), 115 (32), 87 (65), 59 (26). Anal. Calcd for $C_{22}H_{27}NSi$: C, 79.22; H, 8.16; N, 4.20. Found: C, 79.17; H, 8.26; N, 4.20.

***N*,*N*-Dimethyl-4-[(triethylsilyl)methyl]pyridin-3-amine (2g).**



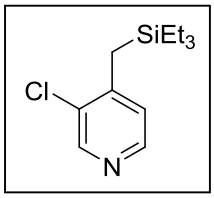
2g was obtained by flash column chromatography on silica-gel (R_f = 0.14 in hexane/EtOAc = 5/1) in 73% yield as a pale yellow oil. Analytically pure sample was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.09 in hexane). ^{1}H NMR ($CDCl_3$) δ: 0.49 (q, *J* = 8.0 Hz, 6H), 0.90 (t, *J* = 8.0 Hz, 9H), 2.17 (s, 2H), 2.71 (s, 6H), 6.89 (d, *J* = 5.0 Hz, 1H), 8.10 (d, *J* = 5.0 Hz, 1H), 8.25 (s, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.5, 7.3, 17.6, 44.5, 124.6, 142.1, 144.5, 145.9, 148.0. IR (ATR): 2951 w, 2908 w, 2874 w, 2828 w, 2782 w. MS, *m/z* (EI, relative intensity, %): 250 (M^+, 17), 235 (16), 221 (47), 115 (39), 87 (100), 59 (39). HRMS Calcd for $C_{14}H_{26}N_2Si$ (M^+): 250.1865. Found: 250.1865.

3-Methoxy-4-[(triethylsilyl)methyl]pyridine (2h).



2h was obtained by flash silica-gel column chromatography (R_f = 0.11 in hexane/EtOAc = 2/1) in 73% yield as a pale yellow oil. Analytically pure sample was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.09 in hexane/EtOAc = 30/1). ^{1}H NMR ($CDCl_3$) δ: 0.50 (q, *J* = 7.9 Hz, 6H), 0.91 (t, *J* = 7.9 Hz, 9H), 2.13 (s, 2H), 3.88 (s, 3H), 6.92 (t, *J* = 4.7 Hz, 1H), 8.06 (d, *J* = 4.7 Hz, 1H), 8.10 (s, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.3, 7.3, 15.8, 55.5, 124.2, 132.1, 139.2, 142.3, 153.3. IR (ATR): 2952 w, 2908 w, 2875 w. MS, *m/z* (EI, relative intensity, %): 237 (M^+, 33), 236 (32), 209 (15), 208 (88), 193 (23), 164 (20), 115 (54), 87 (100), 59 (36). HRMS Calcd for $C_{13}H_{23}NOSi$ (M^+): 237.1549. Found: 237.1543.

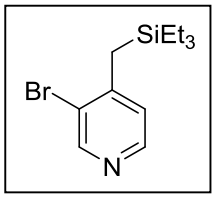
3-Chloro-4-[(triethylsilyl)methyl]pyridine (2i).



2i was obtained by flash column chromatography on silica-gel (R_f = 0.10 in hexane/EtOAc = 10/1) in 60% yield as a pale yellow oil. Analytically pure sample was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.26 in hexane). ^{1}H NMR ($CDCl_3$) δ: 0.57 (q, *J* = 7.9 Hz, 6H), 0.92 (t, *J* = 7.9 Hz, 9H), 2.31 (s, 2H), 6.98 (d, *J* = 5.0 Hz, 1H), 8.25 (d, *J* = 5.0 Hz, 1H), 8.45 (s,

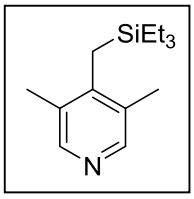
1H). ^{13}C NMR ($CDCl_3$) δ: 3.4, 7.3, 20.0, 124.5, 131.0, 147.0, 148,9, 149.3. IR (ATR): 2953 w, 2909 w, 2876 w. MS, *m/z* (EI, relative intensity, %): 243 (13), 241 (M^+, 38), 212 (25), 156 (13), 115 (53), 87 (100), 59 (26). HRMS Calcd for $C_{12}H_{20}ClNSi$ (M^+): 241.1054. Found: 241.1055.

3-Bromo-4-[(triethylsilyl)methyl]pyridine (2j).



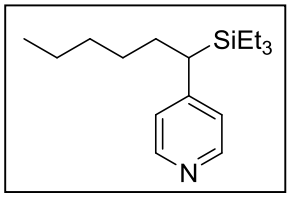
2j was obtained by flash column chromatography on silica-gel (R_f = 0.20 in hexane/EtOAc = 8/1) in 61% yield as a pale yellow oil. Analytically pure sample was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.26 in hexane). ^{1}H NMR ($CDCl_3$) δ: 0.58 (q, *J* = 7.9 Hz, 6H), 0.92 (t, *J* = 7.9 Hz, 9H), 2.34 (s, 2H), 6.99 (d, *J* = 4.8 Hz, 1H), 8.27 (d, *J* = 4.8 Hz, 1H), 8.58 (s, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.5, 7.3, 22.7, 122.4, 124.7, 147.6, 150.8, 151.9. IR (ATR): 2952 w, 2909 w, 2875 w. MS, *m/z* (EI, relative intensity, %): 287 (12), 285 (M^+, 12), 258 (10), 256 (10), 115 (47), 87 (100), 59 (33). HRMS Calcd for $C_{12}H_{20}BrNSi$ (M^+): 285.0548. Found: 285.0551.

3,5-Dimethyl-4-[(triethylsilyl)methyl]pyridine (2k).



2k was obtained by flash column chromatography on silica-gel (R_f = 0.17 in hexane/EtOAc = 1/1) in 50% yield as a pale yellow oil. Analytically pure sample was obtained by column chromatography on NH_2-modified silica-gel (R_f = 0.09 in hexane/EtOAc = 30/1). ^{1}H NMR ($CDCl_3$) δ: 0.56 (q, *J* = 7.9 Hz, 6H), 0.89 (t, *J* = 7.9 Hz, 9H), 2.13 (s, 2H), 2.21 (s, 6H), 8.12 (s, 2H). ^{13}C NMR ($CDCl_3$) δ: 4.8, 7.3, 16.2, 17.6, 129.9, 148.2. 148.3. IR (ATR): 2952 w, 2911 w, 2875 w. MS, *m/z* (EI, relative intensity, %): 236 (18), 235 (M^+, 90), 178 (10), 150 (12), 115 (38), 87 (100), 59 (23). HRMS Calcd for $C_{14}H_{25}NSi$ (M^+): 235.1756. Found: 235.1758.

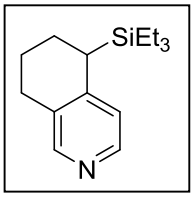
4-[1-(Triethylsilyl)hexyl]pyridine (2l).



2l was obtained by flash column chromatography on silica-gel (R_f = 0.23 in hexane/EtOAc = 5/1) in 50% yield as a pale yellow oil. Analytically pure sample was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.14 in hexane). ^{1}H NMR ($CDCl_3$) δ: 0.51 (q, *J* = 7.9 Hz, 6H), 0.83 (t, *J* = 6.6 Hz, 3H), 0.89 (t, *J* = 7.9 Hz, 9H), 1.05-1.28 (m, 6H), 1.64-1.72 (m, 1H), 1.80-1.90 (m, 1H), 2.18 (dd, *J* = 12.4, 3.1 Hz, 1H), 6.97 (dd, *J* = 4.6, 1.5 Hz, 2H), 8.40 (dd, *J* = 4.6, 1.5 Hz, 2H). ^{13}C NMR ($CDCl_3$) δ: 2.3, 7.6, 14.2, 22.6, 28.9,

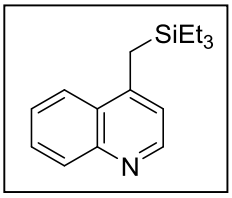
29.2, 31.7, 34.6, 123.4, 149.4, 154.0. IR (ATR): 2953 m, 2928 m, 2874 w. MS, *m/z* (EI, relative intensity, %): 277 (M^+, 2), 234 (10), 221 (23), 220 (100), 115 (54), 87 (98), 59 (64). HRMS Calcd for $C_{17}H_{31}NSi$ (M^+): 277.2226. Found: 277.2225.

5-Triethylsilyl-5,6,7,8-tetrahydroisoquinoline (2m).



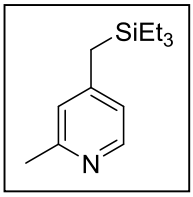
2m was obtained by flash silica-gel column chromatography on (R_f = 0.20 in hexane/EtOAc = 8/1) in 55% yield as a pale yellow oil. Analytically pure sample was obtained by column chromatography on NH_2-modified silica-gel (R_f = 0.13 in hexane/EtOAc = 30/1). ^{1}H NMR ($CDCl_3$) δ: 0.59 (dd, *J* = 15.8, 8.0 Hz, 6H), 0.89 (t, *J* = 8.0 Hz, 9H), 1.81-2.00 (m, 4H), 2.50 (t, *J* = 5.7 Hz, 1H), 2.62-2.78 (m, 2H), 6.86 (d, *J* = 5.0 Hz, 1H), 8.18 (d, *J* = 5.0 Hz, 1H), 8.22 (s, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.1, 7.5, 22.0, 24.2, 25.9, 26.8, 123.0, 132.4, 146.2, 149.6, 150.3. IR (ATR): 2947 w, 2912 w, 2874 w. MS, *m/z* (EI, relative intensity, %): 247 (M^+, 77), 246 (100), 232 (12), 132 (14), 115 (35), 87 (81), 59 (40). HRMS Calcd for $C_{15}H_{25}NSi$ (M^+): 247.1756. Found: 247.1750.

4-[(Triethylsilyl)methyl]quinoline (2n).



2n was obtained by flash column chromatography on silica-gel (R_f = 0.57 in hexane/EtOAc = 1/1) in 62% yield as a pale yellow oil. Analytically pure sample was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.14 in hexane/EtOAc = 6/1). ^{1}H NMR ($CDCl_3$) δ: 0.53 (q, *J* = 7.9 Hz, 6H), 0.89 (t, *J* = 7.9 Hz, 9H), 2.61 (s, 2H), 7.09 (d, *J* = 4.4 Hz, 1H), 7.51-7.53 (m, 1H), 7.66-7.70 (m, 1H), 7.97 (d, *J* = 8.7 Hz, 1H), 8.07 (d, *J* = 8.2 Hz, 1H), 8.70 (d, *J* = 4.4 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.5, 7.3, 18.9, 120.5, 124.2, 125.6, 127.7, 129.0, 130.2, 148.4, 148.5, 149.7. IR (ATR): 2952 w, 2908 w, 2875 w. MS, *m/z* (EI, relative intensity, %): 257 (M^+, 39), 143 (21), 115 (59), 87 (100), 59 (32). HRMS Calcd for $C_{16}H_{23}NSi$ (M^+): 257.1600. Found: .257.1595.

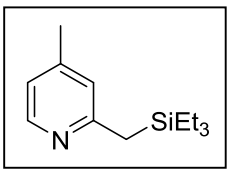
2-Methyl-4-[(triethylsilyl)methyl]pyridine (2o).



2o was obtained by flash column chromatography on silica-gel (R_f = 0.06 in hexane/EtOAc = 5/1) in 72% yield as a pale yellow oil. Analytically pure sample was obtained by column chromatography on NH_2-modified silica-gel (R_f = 0.13 in hexane/EtOAc = 6/1). ^{1}H NMR ($CDCl_3$) δ: 0.52 (q, *J* = 8.0 Hz, 6H), 0.92 (t, *J* = 8.0 Hz, 9H), 2.06 (s, 2H), 2.48 (s, 3H), 6.74 (d, *J* = 5.0 Hz, 1H), 6.80 (s,

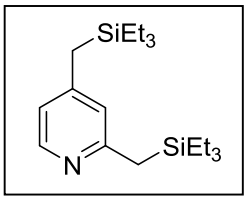
1H), 8.26 (d, J = 5.0 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.0, 7.3, 22.0, 24.4, 120.9, 123.1, 148.7, 150.9, 157.8. IR (ATR): 2952 w, 2910 w, 2876 w. MS, *m/z* (EI, relative intensity, %): 222 (12), 221 (M^+, 62), 164 (12), 136 (21), 115 (49), 87 (100), 59 (23). HRMS Calcd for $C_{13}H_{23}NSi$ (M^+): 221.1600. Found: 221.1597.

Alternative Sample Preparation of 4-Methyl-2-[(triethylsilyl)methyl]pyridine (2o").



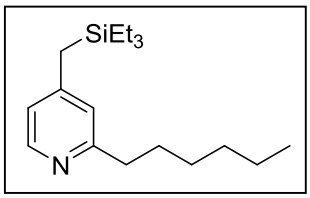
2o" was produced by the lithiation of **1o** (1.1 mL, 10 mmol) with 1.6 M BuLi (6.3 mL, 10 mmol) to generate 2-lithiomethyl-4-methylpyridine,[34] and subsequent trapping with chlorotriethylsilane (1.7 mL, 10 mmol). The product was isolated by flash column chromatography on NH_2-modified silica-gel (R_f = 0.29 in hexane/EtOAc = 10/1) in 63% yield (1.40 g, 6.33 mmol) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.54 (q, J = 7.9 Hz, 6H), 0.90 (t, J = 7.9 Hz, 9H), 2.27 (s, 3H), 2.31 (s, 2H), 6.79 (s, 2H), 8.27-8.27 (m, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.4, 7.3, 21.0, 25.2, 120.3, 123.1, 146.6, 148.8, 161.4. IR (ATR): 2952 w, 2909 w, 2874 w. MS, *m/z* (EI, relative intensity, %): 221 (M^+, 3), 220 (10), 193 (19), 192 (100), 164 (14), 137 (11), 136 (10), 134 (16). HRMS Calcd for $C_{13}H_{23}NSi$ (M^++1): 222.1678. Found: 222.1681.

Alternative Sample Preparation of 2,4-Bis[(triethylsilyl)methyl]pyridine (2o"').



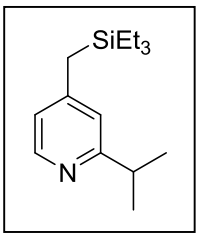
2o"' was produced by the $Ir_4(CO)_{12}$-catalyzed silylation of **2o** (437 mg, 0.97 mmol) at the 2-position with $HSiEt_3$ (320 μL, 2 mmol) in the presence of norbornene (188 mg, 2 mmol) at 160 °C for 20 h. The product was isolated by flash column chromatography on silica-gel (R_f = 0.11 in hexane/EtOAc =10/1) in 31% yield (101 mg) as a pale yellow oil. ^{1}H NMR ($CDCl_3$) δ: 0.51-0.55 (m, 12H), 0.90-0.94 (m, 18H), 2.03 (s, 2H), 2.28 (s, 2H), 6.63-6.64 (m, 2H), 8.19 (dd, J = 4.4, 1.6 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.1, 3.4, 7.4, 21.9, 25.2, 119.6, 122.1, 148.6, 150.2, 161.1. IR (ATR): 2952 w, 2909 w, 2874 w. MS, *m/z* (EI, relative intensity, %): 335 (M^+, 7), 334 (11), 308 (10), 307 (32), 306 (100), 251 (18), 192 (12), 115 (11), 87 (41), 59 (23). HRMS Calcd for $C_{19}H_{37}NSi_2$ (M^+): 335.2465. Found: 335.2469.

2-Hexyl-4-[(triethylsilyl)methyl]pyridine (2p).



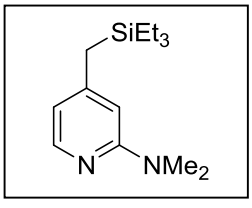
2p was obtained by flash column chromatography on silica-gel (R_f = 0.31 in hexane/EtOAc = 6/1) in 59% yield as a pale yellow oil. Analytically pure sample was obtained by column chromatography on NH_2-modified silica-gel (R_f = 0.29 in hexane/EtOAc = 30/1). ^{1}H NMR ($CDCl_3$) δ: 0.51 (q, *J* = 7.9 Hz, 6H), 0.88-0.92 (m, 12H), 1.21-1.39 (br m, 6H), 1.65-1.73 (quintet, *J* = 7.6 Hz, 2H), 2.08 (s, 2H), 2.70 (t, *J* = 7.6 Hz, 2H), 6.75 (d, *J* = 5.5 Hz, 1H), 6.79 (s, 1H), 8.29 (d, *J* = 5.5 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.0, 7.3, 14.2, 22.1, 22.7, 29.2, 30.1, 31.9, 38.5, 121.0, 122.6, 148.8, 150.7, 162.0. IR (ATR): 2952 w, 2926 w, 2875 w, 2857 w. MS, *m/z* (EI, relative intensity, %): 291 (M^+, 3), 248 (14), 234 (31), 222 (20), 221 (100), 206 (11), 120 (10), 115 (25), 107 (24), 87 (63), 59 (23). HRMS Calcd for $C_{18}H_{33}NSi$ (M^+): 291.2382. Found: 291.2382.

2-Isopropyl-4-[(triethylsilyl)methyl]pyridine (2q).



2q was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.11 in hexane) in 60% yield as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.51 (q, *J* = 8.0 Hz, 6H), 0.92 (t, *J* = 8.0 Hz, 9H), 1.28 (d, *J* = 6.9 Hz, 6H), 2.09 (s, 2H), 2.98 (septet, *J* = 6.9 Hz, 1H), 6.75 (d, *J* = 5.0 Hz, 1H), 6.82 (s, 1H), 8.30 (d, *J* = 5.0 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.0, 7.3, 22.2, 22.7, 36.3, 120.5, 121.2, 148.7, 150.8, 166.9. IR (ATR): 2955 w, 2909 w, 2875 w. MS, *m/z* (EI, relative intensity, %): 250 (11), 249 (M^+, 50), 234 (10), 192 (11), 164 (13), 115 (70), 88 (11), 87 (100), 59 (24). HRMS Calcd for $C_{15}H_{27}NSi$ (M^+): 249.1913. Found: 249.1911.

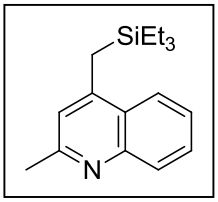
***N*,*N*-Dimethyl-4-[(triethylsilyl)methyl]pyridin-2-amine (2r).**



2r was obtained by flash column chromatography on silica-gel (R_f = 0.31 in hexane/EtOAc = 6/1) in 43% yield as a pale yellow oil. Analytically pure sample was obtained by column chromatography on NH_2-modified silica-gel (R_f = 0.09 in hexane). ^{1}H NMR ($CDCl_3$) δ: 0.53 (q, *J* = 7.9 Hz, 6H), 0.94 (t, *J* = 7.9 Hz, 9H), 2.02 (s, 2H), 3.05 (s, 6H), 6.17 (s, 1H), 6.25 (d, *J* = 5.3 Hz, 1H), 7.97 (d, *J* = 5.3 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.2, 7.4, 22.3, 38.3, 105.1, 112.8, 147.4, 151.2, 159.8. IR (ATR): 2949 w, 2911 w, 2871 w. MS, *m/z* (EI, relative intensity, %): 251 (17), 250 (M^+, 80), 235 (35), 222 (20), 221 (100), 206 (14), 193 (20), 178 (10), 165 (17), 134 (38), 120 (11), 115 (34), 87 (100), 75 (10), 59 (32). HRMS Calcd for $C_{14}H_{26}N_2Si$ (M^+): 250.1865. Found:

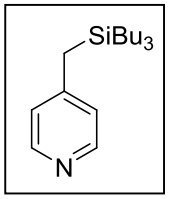
250.1865.

2-Methyl-4-[(triethylsilyl)methyl]quinoline (2s).



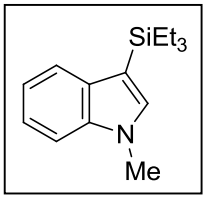
2s was obtained by flash column chromatography on silica-gel (R_f = 0.20 in hexane/EtOAc = 1/10) in 52% yield as a pale yellow oil. Analytically pure sample was obtained by bulb-to-bulb distillation (142 °C/0.9 mmHg). ^{1}H NMR ($CDCl_3$) δ: 0.58 (q, *J* = 7.9 Hz, 6H), 0.93 (t, *J* = 7.9 Hz, 9H), 2.51 (s, 2H), 2.64 (s, 3H), 6.96 (s, 1H), 7.44 (t, *J* = 8.0 Hz, 1H), 7.62 (t, *J* = 8.0 Hz, 1H), 7.91 (d, *J* = 8.0 Hz, 1H), 7.95 (d, *J* = 8.0 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.6, 7.4, 18.8, 26.7, 122.5, 123.6, 124.7, 126.0, 128.9, 129.0, 143.4, 148.1, 162.0. IR (ATR): 2951 w, 2908 w, 2874 w. MS, *m/z* (EI, relative intensity, %): 271 (M^+, 23), 270 (34), 243 (24), 242 (100), 184 (24). HRMS Calcd for $C_{17}H_{25}NSi$ (M^+): 271.1756. Found: 271.1754.

4-[(Tributylsilyl)methyl]pyridine (3a).



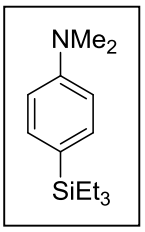
3a was obtained by flash column chromatography on NH_2-modified silica-gel ((R_f = 0.20 in hexane/EtOAc = 30/1) in 65% yield as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.50 (t, *J* = 8.2 Hz, 6H), 0.87 (t, *J* = 7.1 Hz 9H), 1.21-1.32 (m, 12H), 2.10 (s, 2H), 6.92 (d, *J* = 6.0 Hz, 2H), 8.37 (d, *J* = 6.0 Hz, 2H). ^{13}C NMR ($CDCl_3$) δ: 11.7, 13.8, 23.2, 26.0, 26.8, 123.7, 149.4, 150.7. IR (ATR): 2955 w, 2921 w, 2870 w, 2858 w. MS, *m/z* (EI, relative intensity, %): 292 (19), 291 (M^+, 78), 178 (12), 144 (13), 143 (100), 122 (23), 120 (15), 101 (68), 87 (41), 73 (19), 59 (42). Anal. Calcd for $C_{18}H_{33}NSi$: C, 74.15; H, 11.41; N, 4.80. Found: C, 73.81; H, 11.62; N, 4.89.

1-Methyl-3-triethylsilyl-1*H*-indole (5).[7i]



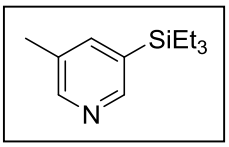
5 was obtained by flash column chromatography on silica-gel (R_f = 0.29 in hexane/EtOAc/Et_3N =20/1/1) in 44% yield as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.86 (q, *J* = 7.7 Hz, 6H), 0.99 (t, *J* = 7.7 Hz, 9H), 3.79 (s, 3H), 7.04 (s, 1H), 7.11 (d, *J* = 7.3 Hz, 1H), 7.22 (t, *J* = 7.1 Hz, 1H), 7.32 (d, *J* = 8.2 Hz, 1H), 7.68 (d, *J* = 7.8 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 4.43, 7.30, 32.9, 105.7, 109.4, 119.3, 121.5, 122.3, 133.4, 136.1, 138.4.

***N*,*N*-Dimethyl-4-(triethylsilyl)aniline (7).[7b]**



7 was obtained by flash column chromatography on silica-gel (R_f = 0.31 in hexane/EtOAc =12/1) in 10% yield as a pale yellow oil. ^{1}H NMR ($CDCl_3$) δ: 0.75 (q, *J* = 7.8 Hz, 6H), 0.96 (t, *J* = 7.8 Hz, 10H), 2.96 (s, 6H), 6.74 (d, *J* = 8.8 Hz, 2H), 7.37 (dt, *J* = 8.8, 2.2 Hz, 2H). ^{13}C NMR ($CDCl_3$) δ: 3.73, 7.69, 40.4, 111.2, 122.4, 135.4, 150.9.

Alternative Sample Preparation of 3-Methyl-5-(triethylsilyl)pyridine.



The procedure with 3-bromo-5-methylpyridine (340 mg, 1.98 mmol) as a starting material, reported by Reuman,[35] was modified using chlorotriethylsilane (340 μL, 2.0 mmol) in place of chlorotrimethylstannane to produce the title compound, which was isolated by flash column chromatography on NH_2-modified silica-gel (R_f = 0.20 in hexane/EtOAc =10/1) in 29% yield (112 mg, 0.58 mmol) as a pale yellow oil. ^{1}H NMR ($CDCl_3$) δ: 0.81 (q, *J* = 7.7 Hz, 6H), 0.97 (t, *J* = 7.7 Hz, 9H), 2.33 (s, 3H), 7.26 (s, 1H), 8.41 (s, 1H), 8.45 (s, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.2, 7.3, 18.7, 131.5, 132.3, 142.4, 150.5, 151.8. IR (ATR): 2953 w, 2910 w, 2875 w. MS, *m/z* (EI, relative intensity, %): 207 (M^+, 7), 178 (65), 151 (12), 150 (100), 122 (72). HRMS Calcd for $C_{12}H_{21}NSi$ (M^+): 207.1443. Found: 207.1441.

1.5 References and Notes

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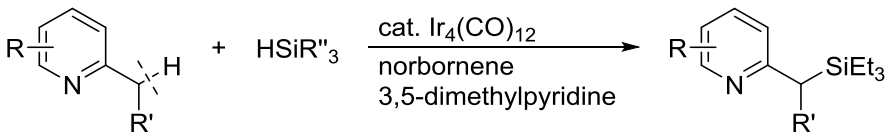
Chapter 2

$Ir_4(CO)_{12}$-Catalyzed Benzylic C(sp^3)-H Silylation of 2-Alkylpyridines with Hydrosilanes Leading to 2-(1-Silylalkyl)pyridines

2.1 Introduction

As described in the general introduction, there is only one example of the direct C(sp^3)-H silylation of 2-alkylpyridine at the α-positions with $HSiEt_3$ catalyzed by potassium *tert*-butoxide.[1] In this reaction, the product yield was moderate, which probably proceeded via a radical chain mechanism[2] and/or the mechanism involving a pentacoordinate silicon species as a key intermediate.[3] In the course of the study of C(sp^3)-H silylation of 4-alkylpyridine, described in Chapter 1, when 2,4-dimethylpyridine was used as a substrate, a trace amount of a product in which the methyl group was silylated at the 2-position was also found in the reaction mixture. This motivated me to explore the reactivity of α-C-H silylation of C2-substituents in pyridine. Chapter 2 describes the C (sp^3)-H silylation of 2-alkylpyridines with hydrosilanes, leading to the formation of 2-(1-silylalkyl)pyridines, catalyzed by an iridium complex/3,5-dimethylpyridine system (scheme 1).

Scheme 1. $Ir_4(CO)_{12}$-Catalyzed Benzylic C(sp^3)-H Silylation of 2-Alkylpyridines with Hydrosilanes

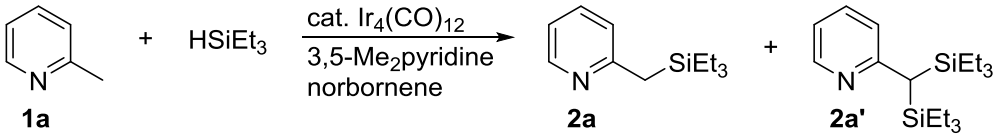


2.2 Results and Discussion

After a series of explorative experiments intended to optimize the reaction conditions, the reaction of 2-methylpyridine (**1a**) with triethylsilane in the presence $Ir_4(CO)_{12}$, norbornene, and 3,5-dimethylpyridine in the absence of a solvent, at 160 ºC for 40 h under a N_2 atmosphere, afforded a mixture of the desired product **2a** (67%, Table 1, entry 1), the disilylation product **2a'** (16%), and the unreacted **1a** (8%). Both **2a** and **2a'** were isolated by flash chromatography on NH_2-modified silica-gel in 59% and 16%, respectively, as the sole products. Deviation from these optimized reaction conditions led to decreased yields. Decreasing the reaction temperature

to 140 ºC and the use of toluene as a solvent resulted in a decrease in the yield of **2a** in 38% and 22%, respectively (entries 2 and 3). As is the case with the previous report on the catalytic C(sp^3)-H silylation of 4-alkylpyridines, the addition of both norbornene (entry 4) and 3,5-dimethylpyridine (entry 5) was required for the reaction to proceed. Screening some catalysts revealed that Ir(acac)$(CO)_2$ (entry 6) and $[Ir(OMe)(cod)]_2$ under an atmosphere of CO (entry 8, versus entry 7) showed catalytic activity in the reaction, indicating that CO is also an essential ligand for the reaction. Transition metal carbonyls other than $Ir_4(CO)_{12}$, such as $Rh_4(CO)_{12}$ (entry 9) and $Ru_3(CO)_{12}$ (entry 10), were also found to be effective catalysts for the reaction. When triphenylsilane was used in the present reaction, **3a** was produced in 80% yield, as determined from the ^{1}H NMR spectrum (entry 11). However, when the product was isolated by NH_2-modified silica-gel column chromatography, the yield of **3a** was decreased significantly, to 54%, probably due to its susceptibility to hydrolysis while it was on the silica-gel column. On the other hand, when $HSi(OEt)_3$ was used in the reaction, the product was not produced.

Table 1. Optimization of the Reaction Conditions[a]

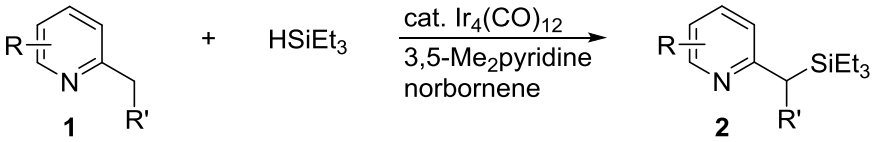


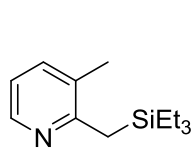
entry	deviation from the standard reaction conditions	yields (%)[b]		
		2a	**2a'**	**1a**
1	None	67 (59)[c]	16 (16)[c]	8
2	At 140 °C	38	7	34
3	In toluene (0.5 mL)	22	2	73
4	Without norbornene	24	trace	30
5	Without 3,5-dimethylpyridine	11	0	74
6	Ir(acac)$(CO)_2$ (0.05 mmol)	54	8	16
7	$[Ir(OMe)(cod)]_2$ (0.025 mmol)	0	0	79
8	$[Ir(OMe)(cod)]_2$ (0.025 mmol) under CO (1 atm)	63	6	15
9	$Rh_4(CO)_{12}$ (0.0125 mmol)	61	9	11
10	$Ru_3(CO)_{12}$ (0.017 mmol)	32	3	57
11	$HSiPh_3$ in place of $HSiEt_3$	80 (54, **3a**)	0	8

[a]Reaction conditions: **1a** (0.5 mmol), $HSiEt_3$ (1 mmol), $Ir_4(CO)_{12}$ (0.0125 mmol), norbornene (1 mmol), and 3,5-dimethylpyridine (0.1 mmol) 160 ºC for 40 h under N_2. [b]Yields of **2a** and **2a'** were determined from ^{1}H NMR spectra with 1,3-dihydro-2-benzofuran as an internal standard. The yield of the unreacted **1a** was determined by GC with tridecane as an internal standard. [c]The number shown in parentheses is the isolated yield.

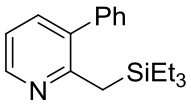
With the optimized reaction conditions in hand, the author next evaluated the substrate scope of the C(sp^3)-H silylation of **1b-1o**, and the results are shown in Table 2. When a 2-methylpyridne derivative containing a methyl group at the 3-position was used, no silylation occurred at this position, and **2b** was isolated in 75% yield. Further silylation of **2b** to produce **2b'** also did not occur, probably due to steric hindrance by the methyl group at the 3-position. Although the author did not examine the reactions of 4-methyl- and 4-primary alkyl-substituted 2-methylpyridines, because the benzylic C-H bond in the 4-substituents were readily silylated,[18] the 4-isopropyl-substituted derivatives **1d** could be applied to the reaction to afford the desired product **2d** in 64%, along with the formation of **2d'** in 4% yield. The reactions of 2-methylpyridines bearing substituents such as methyl (**1e**), phenyl (**1f**), and dimethylamino (**1g**) groups at the 5-position gave, as suspected, a mixture of the monosilylated and disilylated products. In the case of 2-methyl-5-phenoxypyridine (**1h**), **2h** was isolated in 39% yield, along with **1h** being recovered in 53% yield. Efforts to increase the product yield of **2h** were in vain. Ethyl-, hexyl-, and β-phenetyl-substituted pyridines at the 2-position (**1i-1k**), reacted to produce **2i**, **2j**, and **2k** in 71%, 58%, and 57% yield, respectively, and no silylated compound at the homobenzylic position was observed in any of these cases.[4] The 6-membered ring-fused pyridine, **1l**, also underwent regioselective silylation to give **2l** in 73% yield and **2m** was formed from 2-methylquinoline (**1m**) in 66% yield. In the case of harmine (**1n**), a harmala alkaloid belonging to the β-carboline family of compounds, the amount of $HSiEt_3$ was increased to 1.5 equivalent relative to **1n**, because the N-H bond in **1n** was also silylated, and the desired product **2n** was isolated in 86% after chromatographic purification. However, the reaction of 2,6-dimethylpyridine resulted in the quantitative recovery of the starting material. This result indicates that the present reaction proceeds via a mechanism different from that catalyzed by potassium *tert*-butoxide.[1] Although the reaction system was also applicable to the silylation of 2-methylthiazole (**1o**) to afford **2o** in 53% yield, the reaction of 2-methyloxazole gave a complex reaction mixture.

Table 2. Scope of Substrates[a]

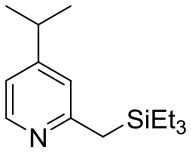




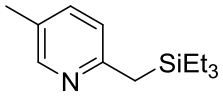
2b, 75%



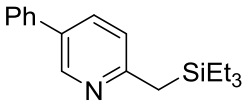
2c, 61%



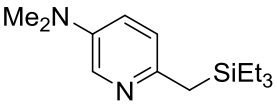
2d, 64% (4%)



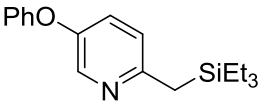
2e, 60% (10%)



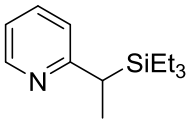
2f, 66% (15%)



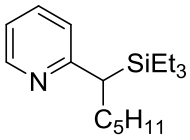
2g, 57% (15%)



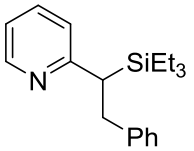
2h, 39%



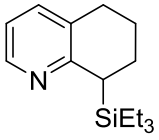
2i, 71%[b]



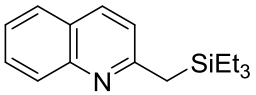
2j, 58%[b]



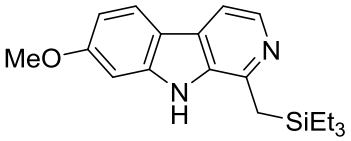
2k, 57%[b]



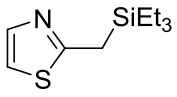
2l, 73%[c]



2m, 66%[c]



2n, 86%[d]



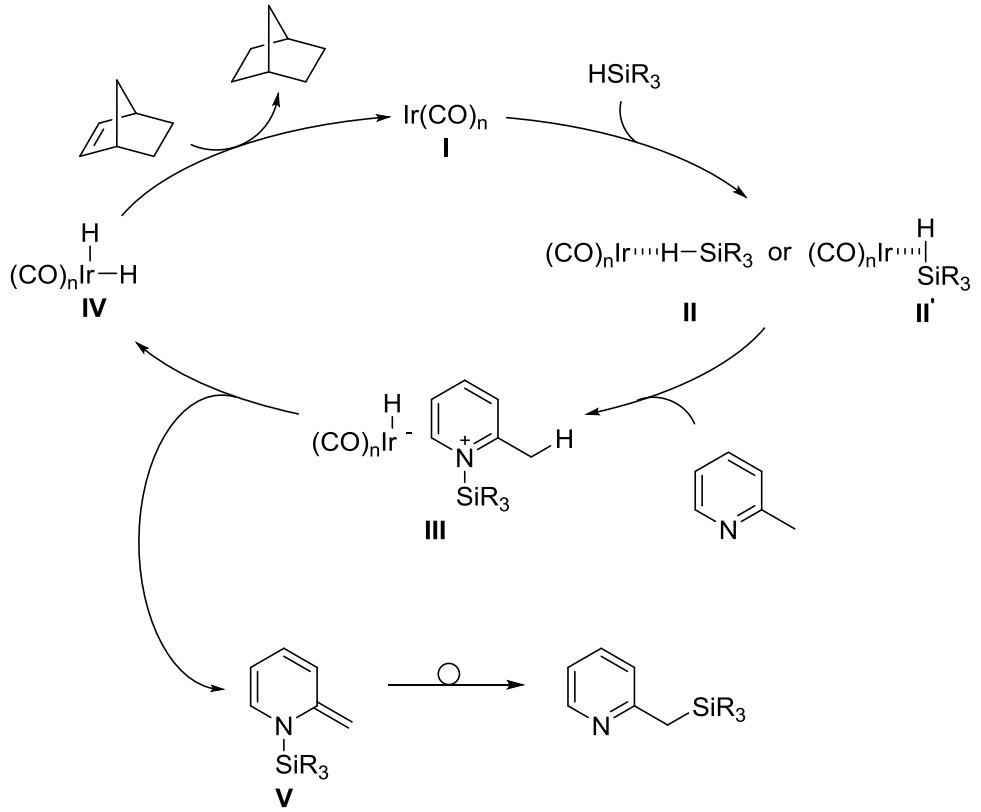
2o, 53%

[a]Reaction conditions: **1** (0.5 mmol), $HSiEt_3$ (1 mmol), $Ir_4(CO)_{12}$ (0.0125 mmol), norbornene (1 mmol), and 3,5-dimethylpyridine (0.1 mmol) 160 ºC for 40 h under N_2. Isolated yields are given. The number shown in parentheses is the isolated yield of disilylation product **2'**. [b]For 4 days. [c]For 3 days. [d]$HSiEt_3$ (1.5 mmol).

A proposed mechanism for the regioselective C(sp^3)-H silylation of 2-alkylpyridines is depicted in Scheme 2, which is almost the same as that proposed in chapter 1, including an electrophilic silicon species as a key intermediate. The coordination of a hydrosilane to an iridium carbonyl complex **I** occurs to form the electrophilic silicon species, either an η^1-silane iridium complex **II** or a σ-silane iridium complex **II'**. Next, the pyridine nitrogen attacks the silicon atom in **II** or **II'** to cleave the Si-H bond heterolytically to form an *N*-silylpyridinium hydridoiridate **III**. Deprotonation at the benzylic position in the *N*-silyl pyridinium by the hydrideiridate then results in the formation of a dihydridoiridium species **IV** and an *N*-silyl enamine **V**. 1,3-Silyl migration[5] of the latter from the nitrogen atom to the carbon atom occurs to produce the desired product. **IV** reacts with norbornene to regenerate the iridium catalyst **I** with the concomitant formation of norbornane. The author speculates that the added 3,5-dimethylpyridine functions as a transporter

of the silyl group via the formation of **III**.[6] The reason that the present reaction requires higher reaction temperature of 160 ºC can be attributed to the steric hindrance around the alkyl group at the 2-position for the abstraction of the benzylic proton in **III**. The possibility that the methyl group at the 2-position hinders the formation of **III** by steric hindrance can be ruled out. This is because, as described in chapter 1, a 2-methyl substituted silylpyridinium species is likely to be generated in the catalytic cycle under the almost same reaction conditions at a reaction temperature of 100 ºC, leading to the C(sp^3)-H silylation of methyl group at the 4-position of 2,4-dimethylpyridine. On the other hand, the decreased reaction rate in the case of the reactions of **2i-2m** and the fact that 2,6-dimethylpyridine failed to participate in the reaction might be also related, partly or significantly, to steric hindrance by the substituents adjacent to the pyridine nitrogen atom to form **III**.

Scheme 2. A Plausible Reaction Mechanism



2.3 Conclusion

The author has demonstrated the iridium-catalyzed regioselective C(sp^3)-H silylation of 2-alkylpyridines with hydrosilanes at the benzylic position. Both norbornene and 3,5-dimethylpyridine are essential additives for the reaction to proceed. $Ir_4(CO)_{12}$ and Ir(acac)$(CO)_2$, and [Ir(OMe)(cod)]$_2$ under ambient atmosphere of CO all showed catalytic activity for the reaction, which indicates that carbon monoxide plays an important role in the catalytic cycle by functioning as a ligand. Other transition metal carbonyls such as $Rh_4(CO)_{12}$ and $Ru_3(CO)_{12}$ can also be used as catalysts for the present C-H silylation. The formation of an electrophilic silicon species is likely to be involved in the reaction as a key intermediate in the catalytic cycle. The added 3,5-dimethylpyridine is thought to serve as the transporter of the silyl group to form a silylpyridinium intermediate.

2.4 Experimental Section

General Information.

^{1}H and ^{13}C NMR spectra were recorded on 400, and 100 MHz spectrometers, respectively, using $CDCl_3$ as the solvent. Data are recorded as follows: chemical shifts in ppm (δ), multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, c = complex), coupling constant (Hz), and integration. Infrared spectra (IR) were recorded by an ATR technique. Absorption data are reported in reciprocal centimeters with the following relative intensities: s (strong), m (medium), or w (weak). Mass spectra were obtained using a spectrometer with a quadrupole mass analyzer at 70 eV. High-resolution mass spectra (HRMS) were obtained using a spectrometer with a double-focusing mass analyzer. Analytical gas chromatography (GC) was carried out on a chromatograph equipped with a flame ionization detector. Melting points were determined on a capillary point apparatus equipped with a digital thermometer and are uncorrected.

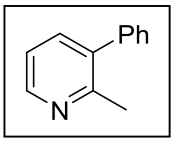
Materials.

Toluene was purified by passage through activated alumina under a positive pressure of N_2. Norbornene and **1n** were purchased and were used as received. Other organic compounds, except **1c**, **1d**, **1f**-**1h**, **1j**, and **1k** were purchased from commercial sources and distilled over CaH_2 before use. Compounds **1c**, **1d**, **1g**, and **1h** were prepared as described below. Compounds **1f**,[7] **1j**,[8] and **1k**[9] were prepared following procedure described in the literature. All metal complexes were purchased from commercial sources and used without further purification.

Typical Procedure for the $Ir_4(CO)_{12}$-Catalyzed C-H Silylation of 2-Alkylpyridines with Hydrosilanes.

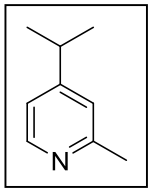
A 8 mL Schlenk tube was flame-dried and purged with N_2. After cooling to room temperature, $Ir_4(CO)_{12}$ (13.8 mg, 0.0125 mmol), 3,5-dimethylpyridine (11 mg, 0.1 mmol), hydrosilane (1 mmol), **1** (0.5 mmol), and norbornene (94 mg, 1 mmol) were placed in the Schlenk tube. The reaction mixture was stirred at 160 °C for 40 h. After cooling to room temperature, the volatiles were removed *in vacuo.* The product was isolated by flash column chromatography on silica-gel and subsequent filtration through a pad of NH_2-modified silica-gel to remove silicon impurities.

2-Methyl-3-phenylpyridine (1c).[10]



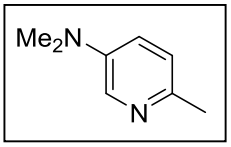
The procedure reported by Tobisu and Chatani[11] was modified by using 3-bromo-2-methylpyridine (0.86 g, 5.0 mmol) in place of (2-bromophenyl)phenyl sulfide to produce **1c**, which was isolated by distillation under reduced pressure (140 °C/5 mmHg) in 82% yield (0.69 g, 4.1 mmol) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 2.51 (s, 3H), 7.18 (dd, *J* = 7.8, 4.7 Hz, 1H), 7.31-7.32 (m, 2H), 7.35-7.39 (m, 1H), 7.42-7.45 (m, 2H), 7.51 (dd, *J* = 7.8, 1.7 Hz, 1H), 8.50 (dd, *J* = 4.7, 1.7 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 23.5, 121.1, 127.6, 128.5, 129.1, 137.1, 137.3, 140.1, 148.0, 155.9.

4-Isopropyl-2-methylpyridine (1d).[12]



The procedure reported by Comins[12] was modified by using DDQ[13] in place of sulfur for the aromatization of dihydropyridine. **1d** was isolated from the crude product by distillation under reduced pressure (58 °C/3.2 mmHg) in 6% yield (173.5 mg, 1.28 mmol) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 1.24 (d, *J* = 6.9 Hz, 6H), 2.53 (s, 3H), 2.79-2.89 (m, 1H), 6.94 (d, *J* = 5.3 Hz, 1H), 7.00 (s, 1H), 8.36 (d, *J* = 5.3 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 23.2, 24.5, 33.6, 119.2, 121.6, 149.1, 157.9, 158.3.

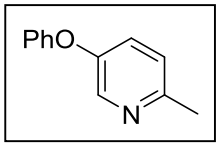
***N*,*N*-6-Trimethylpyridin-3-amine (1g)**.[14]



The procedure reported by Aron[15] was modified by using 2-methylpyridin-5-amine (1.00 g, 9.2 mmol) in place of pyridin-3-amine to produce **1g**, which was isolated by distillation under reduced pressure (57 °C/1.2 mmHg) in 61% yield (0.76 g, 5.60 mmol) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 2.45 (s, 3H), 2.93 (s, 6H), 6.95 (dd, *J* = 8.5, 3.0 Hz, 1H), 6.99 (d, *J* = 8.5 Hz, 1H), 8.04 (d, *J* = 3.0 Hz, 1H). ^{13}C NMR ($CDCl_3$)

δ: 23.1, 40.5, 120.2, 122.9, 134.5, 144.4, 146.0.

2-Methyl-5-phenoxypyridine (1h).[16]

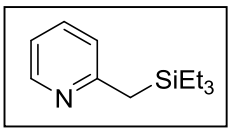


The procedure reported by Olofsson[17] was modified by using 6-methylpyridin-3-ol (1.39 g, 12.8 mmol) in place of pyridin-3-ol to produce **1h**, which was isolated by distillation under reduced pressure (85 °C/0.8 mmHg) in 81% yield (1.92 g, 10.4 mmol) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 2.55 (s, 3H), 6.99 (dd, *J* = 8.7, 0.9 Hz, 2H), 7.10-7.14 (m, 2H), 7.22 (dd, *J* = 8.2, 2.7 Hz, 1H), 7.32-7.37 (m, 2H), 8.30 (d, *J* = 2.7 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 23.7, 118.3, 123.5, 123.7, 126.6, 129.9, 140.9, 151.3, 153.2, 157.0.

2-[(Triethylsilyl)methyl]pyridine (2a).

After reacting **1a** (46.3 mg, 0.50 mmol) under the standard reaction conditions, the reaction mixture was passed through a flash silica-gel column to separate **2a** (62.2 mg, R_f = 0.17 in hexane/EtOAc = 20/1) and 2-[bis(triethylsilyl)methyl]pyridine (**2a'**) (32.2 mg, R_f = 0.46 in hexane/EtOAc = 20/1), although both products still contained some silicon impurities.

*2-[(Triethylsilyl)methyl]pyridine (**2a**).*

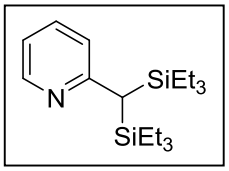


The crude mixture containing **2a** (62.2 mg) was subsequently filtered through a pad of NH_2-modified silica-gel (1.8 cm id × 5 cm h) using 120 mL of hexane as the eluent to give pure **2a** in 59% yield (60.9 mg) as a colorless oil.^{1}H NMR ($CDCl_3$) δ: 0.54 (q, *J* = 8.0 Hz, 6H), 0.90 (t, *J* = 8.0 Hz, 9H), 2.36 (s, 2H), 6.95-6.97 (m, 2H), 7.48 (td, *J* = 7.8, 1.8 Hz, 1H), 8.41 (d, *J* = 4.6 Hz, 1H) ^{13}C NMR ($CDCl_3$) δ: 3.4, 7.4, 25.5, 119.2, 122.4, 136.0, 149.0, 161.7. IR (ATR): 2952 w, 2909 w, 2874 w. MS, *m/z* (CI, relative intensity, %): 208 ([M+H]$^+$, 100), 178 (12). HRMS Calcd for $C_{12}H_{22}NSi$ ([M+H]$^+$): 208.1522. Found: 208.1525.

*2-[Bis(triethylsilyl)methyl]pyridine (**2a'**).*

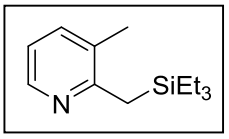
The crude mixture containing **2a'** (32.2 mg) was subsequently filtered through a pad of NH_2-modified silica-gel (1.8 cm id × 5 cm h) using 120 mL of hexane as the eluent to give pure **2a'** in 16% yield (26.2 mg) as a colorless oil. However, since **2a'** gradually decomposed during handling, it was not possible to collect spectroscopic spectra, except for ^{1}H NMR. Therefore, we modified the procedure for producing **2a'** as the major product by using an excess amount of $HSiEt_3$ and norbornene. Details are described below.

2-[Bis(triethylsilyl)methyl]pyridine (2a').



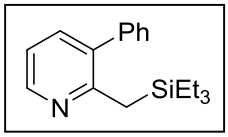
2a' was produced by the present $Ir_4(CO)_{12}$-catalyzed reaction of **1a** (46.6 mg, 0.50 mmol) with $HSiEt_3$ (480 mL, 3.00 mmol) in the presence of norbornene (282 mg, 3.00 mmol) at 160 ºC for 4 days. The reaction mixture was passed through a flash silica-gel column to separate **2a** (3.1 mg, R_f = 0.17 in hexane/EtOAc = 20/1) and 2-[bis(triethylsilyl)methyl]pyridine (**2a'**) (102.4 mg, R_f = 0.46 in hexane/EtOAc = 20/1), although both products still contained some silicon impurities. The crude mixture containing **2a'** was subsequently filtered through a pad of NH_2-modified silica-gel (1.8 cm id × 5 cm h) using 120 mL of hexane as the eluent to give pure **2a'** in 61% yield (98.2 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.59 (m, 12H), 0.88 (t, *J* = 8.0 Hz, 18H), 2.11 (s, 1H), 6.88-6.92 (m, 2H), 7.41 (td, *J* = 7.7, 1.5 Hz, 1H), 8.38 (d, *J* = 5.0 Hz, 1H).^{13}C NMR ($CDCl_3$) δ: 4.9, 7.9, 26.2, 118.3, 123.3, 135.3, 148.8, 164.1. IR (ATR): 2950 m, 2909 w, 2875 m. MS, *m/z* (CI, relative intensity, %): 322 ($[M+H]^+$, 100), 182 (27). HRMS Calcd for $C_{18}H_{35}NSi_2$ ($[M+H]^+$): 322.2386. Found: 322.2383.

3-Methyl-2-[(triethylsilyl)methyl]pyridine (2b).



2b was obtained by flash column chromatography on silica-gel (R_f = 0.23 in hexane/EtOAc = 12/1) and subsequent filtration through a pad of NH_2-modified silica-gel (1.8 cm id × 5 cm h) using 120 mL of hexane as the eluent in 75% yield (83 mg) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 0.57 (q, *J* = 7.9 Hz, 6H), 0.88 (t, *J* = 7.9 Hz, 9H), 2.25 (s, 3H), 2.36 (s, 2H), 6.90 (dd, *J* = 7.3, 5.0 Hz, 1H), 7.33 (d, *J* = 7.8 Hz, 1H), 8.28 (dd, *J* = 5.0, 1.4 Hz, 1H).^{13}C NMR ($CDCl_3$) δ: 3.9, 7.3, 19.9, 22.5, 119.4, 129.6, 137.1, 146.5, 160.7. IR (ATR): 2951 w, 2909 w, 2874 w. MS, *m/z* (CI, relative intensity, %): 222 ($[M+H]^+$, 100), 192 (12). HRMS Calcd for $C_{13}H_{24}NSi$ ($[M+H]^+$): 222.1678. Found: 222.1676.

3-Phenyl-2-[(triethylsilyl)methyl]pyridine (2c).



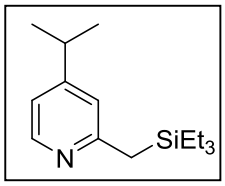
2c was obtained by flash column chromatography on silica-gel (R_f = 0.54 in hexane/EtOAc = 5/1) and subsequent filtration through a pad of NH_2-modified silica-gel (1.8 cm id × 5 cm h) using 120 mL of hexane as the eluent in 61% yield (86.0 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.37 (q, *J* = 7.8 Hz, 6H), 0.69 (t, *J* = 7.8 Hz, 9H), 2.49 (s, 2H), 7.03 (dd, *J* = 7.5, 4.9 Hz, 1H), 7.32-7.36 (m, 3H), 7.39-7.43 (m, 3H), 8.42 (dd, *J* = 4.9, 1.8 Hz, 1H).^{13}C NMR ($CDCl_3$) δ: 3.8, 7.2, 22.4, 119.3, 127.3, 128.5, 129.5,

135.8, 137.3, 140.9, 147.9, 159.7. IR (ATR): 2952 w, 2874 w. MS, *m/z* (CI, relative intensity, %): 284 ([M+H]$^+$, 100), 254 (40). HRMS Calcd for $C_{18}H_{26}NSi$ ([M+H]$^+$): 284.1835. Found: 284.1832.

4-Isopropyl-2-[(triethylsilyl)methyl]pyridine (2d) and 2-[Bis(triethylsilyl)methyl]-4-isopropylpyridine (2d').

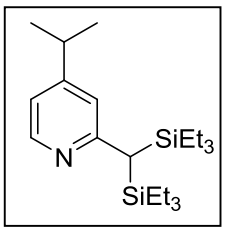
After reacting **1d** (68.5 mg, 0.507 mmol) under the standard reaction conditions, the reaction mixture was passed through a flash silica-gel column to separate **2d** (88.5 mg, R_f = 0.19 in hexane/EtOAc = 20/1) and **2d'** (21.8 mg, R_f = 0.43 in hexane/EtOAc = 20/1), although both products still contained some silicon impurities.

*4-Isopropyl-2-[(triethylsilyl)methyl]pyridine (**2d**).*



The crude mixture containing **2d** (88.5 mg) was subsequently filtered through a pad of NH_2-modified silica-gel (1.8 cm id × 5 cm h) using 120 mL of hexane as the eluent to give pure **2d** in 64% yield (81.2 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.54 (q, *J* = 7.9 Hz, 6H), 0.90 (t, *J* = 7.9 Hz, 9H), 1.22 (d, *J* = 6.9 Hz, 6H), 2.33 (s, 2H), 2.80 (septet, *J* = 6.9 Hz, 1H), 6.82 (d, *J* = 2.3 Hz, 2H), 8.29-8.30 (m, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.4, 7.3, 23.2, 25.4, 33.6, 117.7, 120.5, 149.0, 157.3, 161.5. IR (ATR): 2955 w, 2908 w, 2874 w. MS, *m/z* (EI, relative intensity, %): 249 (M$^+$, 4), 248 (12), 234 (11), 221 (21), 220 (100), 205 (10), 204 (11), 165 (15). HRMS Calcd for $C_{15}H_{27}NSi$ ([M+H]$^+$): 250.1991. Found: 250.1987.

*2-[Bis(triethylsilyl)methyl]-4-isopropylpyridine (**2d'**).*

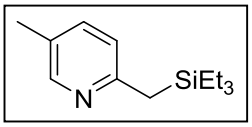


The crude mixture containing **2d'** (21.8 mg) was subsequently filtered through a pad of NH_2-modified silica-gel (1.8 cm id × 5 cm h) using 120 mL of hexane as the eluent to give pure **2d'** in 4% yield (8.2 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.58-0.61 (m, 12H), 0.88 (t, *J* = 7.8 Hz, 18H), 1.21 (d, *J* = 6.9 Hz, 6H), 2.10 (s, 1H), 2.78 (septet, *J* = 6.9 Hz, 1H), 6.75 (dd, *J* = 5.0, 1.8 Hz, 1H), 6.78 (s, 1H), 8.25 (d, *J* = 5.0 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 4.9, 7.9, 23.3, 26.3, 33.6, 117.0, 121.5, 148.8, 156.6, 163.8. IR (ATR): 2953 w, 2911 w, 2875 w. MS, *m/z* (CI, relative intensity, %): 364 ([M+H]$^+$, 100), 334 (28). HRMS Calcd for $C_{21}H_{42}NSi$ ([M+H]$^+$): 364.2856. Found: 364.2854.

5-Methyl-2-[(triethylsilyl)methyl]pyridine (2e) and 2-[Bis(triethylsilyl)methyl]-5-methylpyridine (2e').

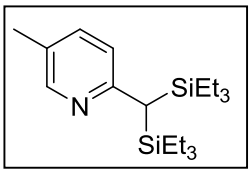
After reacting **1e** (53.6 mg, 0.50 mmol) under the standard reaction conditions, the reaction mixture was passed through a flash silica-gel column to separate **2e** (68.2 mg, R_f = 0.20 in hexane/EtOAc = 12/1) and **2e'** (18.2 mg, R_f = 0.51 in hexane/EtOAc = 12/1), although both products still contained some silicon impurities.

*5-Methyl-2-[(triethylsilyl)methyl]pyridine (**2e**).*



The crude mixture containing **2e** (68.2mg) was subsequently filtered through a pad of NH_2-modified silica-gel (1.8 cm id × 5 cm h) using 120 mL of hexane as the eluent to give pure **2e** in 60% yield (66.8 mg) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 0.53 (q, *J* = 7.9 Hz, 6H), 0.90 (t, *J* = 7.9 Hz, 9H), 2.25 (s, 3H), 2.31 (s, 2H), 6.86 (d, *J* = 7.9 Hz, 1H), 7.30 (dd, *J* = 7.9, 2.2 Hz, 1H), 8.24 (d, *J* = 2.2 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.3, 7.4, 18.0, 24.7, 121.8, 128.1, 136.6, 149.2, 158.4. IR (ATR): 2952 w, 2909 w, 2874 w. MS, *m/z* (CI, relative intensity, %): 222 ($[M+H]^+$, 100), 192 (12). HRMS Calcd for $C_{13}H_{24}NSi$ ($[M+H]^+$): 222.1678. Found: 222.1677.

*2-[Bis(triethylsilyl)methyl]-5-methylpyridine (**2e'**).*

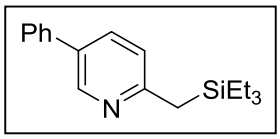


The crude mixture containing **2e'** (18.2 mg) was subsequently filtered through a pad of NH_2-modified silica-gel (1.8 cm id × 5 cm h) using 120 mL of hexane as the eluent to give pure **2e'** in 10% yield (17.4 mg) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 0.54-0.61 (m, 12H), 0.88 (t, *J* = 8.0 Hz, 18H), 2.06 (s, 1H), 2.23 (s, 3H), 6.80 (d, *J* = 7.9 Hz, 1H), 7.22 (dd, *J* = 7.9, 2.2 Hz, 1H), 8.20 (d, *J* = 2.2 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 4.8, 7.9, 18.1, 25.3, 122.8, 127.2, 136.2, 149.1, 160.8. IR (ATR): 2952 m, 2910 w, 2874 w. MS, *m/z* (CI, relative intensity, %): 336 ($[M+H]^+$, 100), 306 (29). HRMS Calcd for $C_{19}H_{38}NSi_2$ ($[M+H]^+$): 336.2543. Found: 336.2539.

5-Phenyl-2-[(triethylsilyl)methyl]pyridine (2f) and 2-[Bis(triethylsilyl)methyl]-5-phenylpyridine (2f').

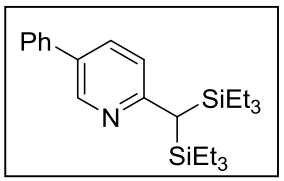
After reacting **1f** (84.4 mg, 0.50 mmol) under the standard reaction conditions, the reaction mixture was passed through a flash silica-gel column to separate **2f** (94.2 mg, R_f = 0.20 in hexane/EtOAc = 12/1) and **2f'** (30.2 mg, R_f = 0.43 in hexane/EtOAc = 12/1), although both products still contained some silicon impurities.

*5-Phenyl-2-[(triethylsilyl)methy])pyridine (**2f**).*



The crude mixture containing **2f** (94.2 mg) was subsequently filtered through a pad of NH_2-modified silica-gel (1.8 cm id × 5 cm h) using 120 mL of hexane as the eluent to give pure **2f** in 66% yield (93.7 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.58 (q, *J* = 8.0 Hz, 6H), 0.93 (t, *J* = 8.0 Hz, 9H), 2.41 (s, 2H), 7.04 (d, *J* = 8.2 Hz, 1H), 7.35 (t, *J* = 7.3 Hz, 1H), 7.45 (t, *J* = 7.5 Hz, 2H), 7.56 (d, *J* = 7.3 Hz, 2H), 7.70 (dd, *J* = 8.2, 2.3 Hz, 1H), 8.67 (d, *J* = 2.7 Hz, 1H).^{13}C NMR ($CDCl_3$) δ: 3.3, 7.4, 25.2, 122.2, 126.8, 127.6, 129.0, 132.0, 134.3, 138.2, 147.4, 160.7. IR (ATR): 2951 w, 2908 w, 2874 w. MS, *m/z* (CI, relative intensity, %): 284 ([M+H]$^+$, 100), 254 (11). HRMS Calcd for $C_{18}H_{26}NSi$ ([M+H]$^+$): 284.1835. Found: 284.1834.

*2-[Bis(triethylsilyl)methyl]-5-phenylpyridine (**2f'**).*

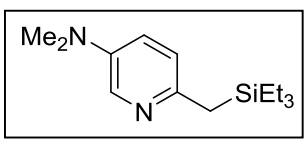


The crude mixture containing **2f'** (30.2 mg) was subsequently filtered through a pad of NH_2-modified silica-gel (1.8 cm id × 5 cm h) using 120 mL of hexane as the eluent to give pure **2f'** in 15% yield (29.0 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.56-0.67 (m, 12H), 0.90 (t, *J* = 7.8 Hz, 18H), 2.16 (s, 1H), 6.97 (d, *J* = 8.0 Hz, 1H), 7.34 (t, *J* = 7.5 Hz, 1H), 7.44 (t, *J* = 7.5 Hz, 2H), 7.58 (d, *J* = 7.5 Hz, 2H), 7.65 (d, *J* = 8.0 Hz, 1H), 8.65 (s, 1H).^{13}C NMR ($CDCl_3$) δ: 4.9, 7.9, 25.9, 123.2, 126.7, 127.4, 129.0, 131.0, 133.7, 138.4, 147.1, 163.2. IR (ATR): 2950 w, 2909 w, 2874 w. MS, *m/z* (CI, relative intensity, %): 398 ([M+H]$^+$, 100), 368 (19). HRMS Calcd for $C_{24}H_{40}NSi_2$ ([M+H]$^+$): 398.2699. Found: 398.2700.

_N_,_N_-Dimethyl-2-[(triethylsilyl)methyl]pyridin-5-amine (2g).

After reacting **1g** (68.3 mg, 0.5 mmol) under the standard reaction conditions, the reaction mixture was passed through a flash silica-gel column to separate **2g** (76.7 mg, R_f = 0.14 in hexane/EtOAc = 6/1) and **2g'** (29.8 mg, R_f = 0.49 in hexane/EtOAc = 6/1), although both products still contained some silicon impurities.

*N,N-Dimethyl-2-[(triethylsilyl)methyl]pyridin-5-amine (**2g**).*



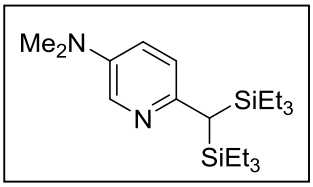
The crude mixture containing **2g** (76.7 mg) was subsequently filtered through a pad of NH_2-modified silica-gel (1.8 cm id × 5 cm h) using 120 mL of hexane as the eluent to give pure **2g** in 57% yield (71.8 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.53 (q, *J* = 7.9 Hz, 6H), 0.91 (t, *J* = 7.9 Hz, 9H), 2.23 (s,

2H), 2.90 (s, 6H), 6.82 (d, J = 8.7 Hz, 1H), 6.92 (dd, J = 8.7, 3.2 Hz, 1H), 8.00 (d, J = 3.2 Hz, 1H).^{13}C NMR ($CDCl_3$) δ: 3.4, 7.5, 23.5, 40.8, 120.7, 122.1, 134.7, 143.5, 149.5. IR (ATR): 2950 w, 2873 w. MS, *m/z* (EI, relative intensity, %): 250 (M^+, 20), 235 (27), 222(21), 221(100), 82(14). HRMS Calcd for $C_{14}H_{26}N_2Si$ (M^+): 250.1865. Found: 250.1862.

*2-[Bis(triethylsilyl)methyl]-N,N-dimethylpyridin-5-amine (**2g'**).*

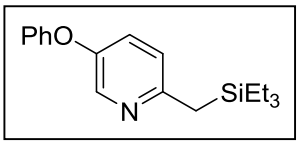
The crude mixture containing **2g'** (29.8 mg) was subsequently filtered through a pad of NH_2-modified silica-gel (1.8 cm id × 5 cm h) using 120 mL of hexane as the eluent to give pure **2g'** in 15% yield (26.6 mg) as a colorless oil. However, since **2g'** gradually decomposed during handling, it was not possible to collect spectroscopic spectra, except for ^{1}H NMR. Therefore, we modified the procedure for producing **2g'** as the major product by using an excess amount of $HSiEt_3$ and norbornene. Details are described below.

2-[Bis(triethylsilyl)methyl]-*N*,*N*-dimethylpyridin-5-amine (2g').



2g' was produced by the present $Ir_4(CO)_{12}$-catalyzed reaction of **1a** (68.1 mg, 0.50 mmol) with $HSiEt_3$ (480 mL, 3.00 mmol) in the presence of norbornene (282 mg, 3.00 mmol) at 160 ºC for 4 days. The reaction mixture was passed through a flash silica-gel column to separate **2g** (6.6 mg, R_f = 0.14 in hexane/EtOAc = 6/1) and **2g'** (108.3 mg, R_f = 0.49 in hexane/EtOAc = 6/1), although both products still contained some silicon impurities. The crude mixture containing **2g'** was subsequently filtered through a pad of NH_2-modified silica-gel (1.8 cm id × 5 cm h) using 120 mL of hexane as the eluent to give pure **2g'** in 57% yield (104.1 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.54-0.62 (m, 12H), 0.88 (t, J = 8.0 Hz, 18H), 1.98 (s, 1H), 2.89 (s, 6H), 6.77 (d, J = 8.7 Hz, 1H), 6.87 (dd, J = 8.7, 3.2 Hz, 1H), 7.98 (d, J = 3.2 Hz, 1H).^{13}C NMR ($CDCl_3$) δ: 4.9, 7.9, 23.7, 40.8, 120.3, 123.0, 134.5, 142.8, 151.8. IR (ATR): 2950 m, 2874 m. MS, *m/z* (CI, relative intensity, %): 365 ($[M+H]^+$, 100), 364 (M^+, 24), 335(18). HRMS Calcd for $C_{18}H_{35}NSi_2$ ($[M+H]^+$): 365.2808. Found: 365.2804.

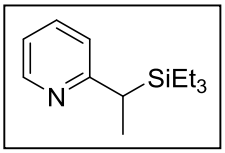
5-Phenoxy-2-[(triethylsilyl)methyl]pyridine (2h).



2h was obtained by flash column chromatography on silica-gel (R_f = 0.50 in hexane/EtOAc = 5/1) and subsequent filtration through a pad of NH_2-modified silica-gel (1.8 cm id × 5 cm h) using 120 mL of hexane as the eluent in 39% yield (59.0 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.59 (q, J = 7.9 Hz,

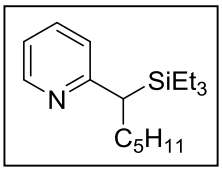
6H), 0.95 (t, J = 7.9 Hz, 9H), 2.37 (s, 2H), 6.96-6.99 (m, 3H), 7.11 (t, J = 7.4 Hz, 1H), 7.19 (dd, J = 8.7, 2.7 Hz, 1H), 7.34 (t, J = 7.4 Hz, 2H), 8.26 (d, J = 2.7 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.4, 7.4, 24.6, 118.1, 122.7, 123.4, 126.9, 129.9, 140.9, 150.2, 156.8, 157.5. IR (ATR): 2952 w, 2874 w. MS, *m/z* (CI, relative intensity, %): 300 ($[M+H]^+$, 100), 270 (14). HRMS Calcd for $C_{18}H_{26}NOSi$ ($[M+H]^+$): 300.1784. Found: 300.1783.

2-[1-(Triethylsilyl)ethyl]pyridine (2i).



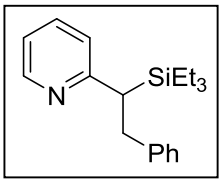
2i was obtained by flash column chromatography on silica-gel (R_f = 0.31 in hexane/EtOAc = 5/1) and subsequent filtration through a pad of NH_2-modified silica-gel (1.8 cm id × 5 cm h) using 120 mL of hexane as the eluent in 71% yield (78.1 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.54 (q, J = 8.0 Hz, 6H), 0.87 (t, J = 8.0 Hz, 9H), 1.43 (d, J = 7.5 Hz, 3H), 2.57 (q, J = 7.5 Hz, 1H), 6.95-7.01 (m, 2H), 7.50 (td, J = 7.5, 1.7 Hz, 1H), 8.45 (d, J = 5.0 Hz, 1H).^{13}C NMR ($CDCl_3$) δ: 2.3, 7.6, 14.5, 30.2, 119.5, 121.6, 135.8, 148.9, 166.2. IR (ATR): 2952 m, 2909 w, 2874 m. MS, *m/z* (CI, relative intensity, %): 222 ($[M+H]^+$, 100), 192 (16). HRMS Calcd for $C_{13}H_{24}NSi$ ($[M+H]^+$): 222.1678. Found: 222.1675.

2-[1-(Triethylsilyl)hexyl]pyridine (2j).



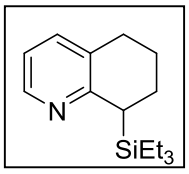
2j was obtained by flash column chromatography on silica-gel (R_f = 0.43 in hexane/EtOAc = 30/1) and subsequent filtration through a pad of NH_2-modified silica-gel (1.8 cm id × 5 cm h) using 120 mL of hexane as the eluent in 58% yield (80.2 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.52 (q, J = 7.8 Hz, 6H), 0.86-0.89 (m, 12H), 1.15-1.22 (m, 6H), 1.65-1.71 (m, 1H), 2.03-2.08 (m, 1H), 2.44 (dd, J = 12.1, 3.0 Hz, 1H), 6.95-7.00 (m, 2H), 7.49 (td, J = 7.7, 2.0 Hz, 1H), 8.47 (d, J = 3.7 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 2.6, 7.6, 14.2, 22.7, 29.2, 31.8, 37.5, 119.4, 122.5, 135.6, 149.1, 164.8. IR (ATR): 2952 w, 2928 w, 2874 w. MS, *m/z* (EI, relative intensity, %): 277 (M^+, 7), 276 (24), 246 (23), 248 (100), 221 (11), 220 (55), 192 (44), 120 (10), 115 (60), 106 (11), 93 (11), 87 (63), 59 (38). HRMS Calcd for $C_{17}H_{32}NSi$ ($[M+H]^+$): 278.2304. Found: 278.2300.

2-[2-Phenyl-1-(triethylsilyl)ethyl]pyridine (2k).



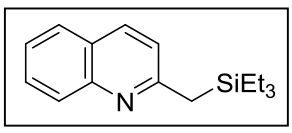
2k was obtained by flash column chromatography on silica-gel (R_f = 0.16 in hexane/EtOAc = 50/1) and subsequent filtration through a pad of NH_2-modified silica-gel (1.8 cm id × 5 cm h) using 120 mL of hexane as the eluent in 57% yield (84.8 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.60 (q, *J* = 7.7 Hz, 6H), 0.91 (t, *J* = 7.7 Hz, 9H), 2.77 (dd, *J* = 11.9, 3.1 Hz, 1H), 3.04 (dd, *J* = 14.5, 3.1 Hz, 1H), 3.42 (dd, *J* = 14.5, 11.9 Hz, 1H), 6.86 (d, *J* = 7.7 Hz, 1H), 6.91-6.93 (m, 1H), 7.02-7.07 (m, 3H), 7.12 (t, *J* = 7.6 Hz, 2H), 7.39 (td, *J* = 7.7, 1.8 Hz, 1H), 8.47 (d, *J* = 3.7 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 2.7, 7.6, 35.3, 39.3, 119.6, 123.1, 125.6, 128.1, 128.5, 135.6, 142.9, 149.1, 163.6. IR (ATR): 2950 w, 2909 w, 2874 w. MS, *m/z* (EI, relative intensity, %): 297 (M^+, 13), 296 (29), 269 (20), 268 (77), 240 (26), 239 (13), 238 (59), 192 (38), 183 (27), 182 (100), 121 (15), 120 (15), 115 (14), 106 (20), 91 (12), 87 (51), 59 (32). HRMS Calcd for $C_{19}H_{28}NSi$ ($[M+H]^+$): 298.1991. Found: 298.1992.

8-(Triethylsilyl)-5,6,7,8-tetrahydroquinoline (2l).



2l was obtained by flash column chromatography on silica-gel (R_f = 0.27 in hexane/EtOAc = 12/1) and subsequent filtration through a pad of NH_2-modified silica-gel (1.8 cm id × 5 cm h) using 120 mL of hexane as the eluent in 73% yield (92.1 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.61 (q, *J* = 7.9 Hz, 6H), 0.86 (t, *J* = 7.9 Hz, 9H), 1.60-1.70 (m, 1H), 1.83-1.88 (m, 2H), 2.02-2.07 (m, 1H), 2.66-2.74 (m, 3H), 6.89 (dd, *J* = 7.3, 4.8 Hz, 1H), 7.24-7.26 (m, 1H), 8.27 (d, *J* = 4.8 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.5, 7.6, 22.6, 25.2, 29.5, 29.7, 119.3, 131.3, 136.2, 146.5, 161.1. IR (ATR): 2947 w, 2911 w, 2873 w. MS, *m/z* (EI, relative intensity, %): 247 (M^+, 19), 246 (66), 219 (32), 218 (100), 205 (26), 191 (23), 190 (12), 288 (11), 163 (29), 132 (25), 87 (37), 59 (32). HRMS Calcd for $C_{15}H_{25}NSi$ (M^+): 247.1756. Found: 247.1750.

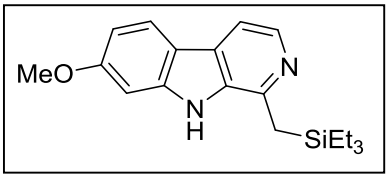
2-[(Triethylsilyl)methyl]quinoline (2m).



2m was obtained by flash column chromatography on silica-gel (R_f = 0.24 in hexane/EtOAc = 10/1) and subsequent filtration through a pad of NH_2-modified silica-gel (1.8 cm id × 5 cm h) using 120 mL of hexane as the eluent in 66% yield (85.6 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.58 (q, *J* = 8.0 Hz, 6H), 0.93 (t, *J* = 8.0 Hz, 9H), 2.57 (s, 2H), 7.11 (d, *J* = 8.2 Hz, 1H), 7.42 (t, *J* = 7.7 Hz, 1H), 7.63

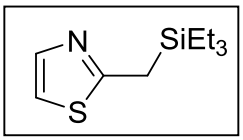
(t, *J* = 7.7 Hz, 1H), 7.72 (d, *J* = 8.2 Hz, 1H), 7.95 (d, *J* = 7.7 Hz, 2H). ^{13}C NMR ($CDCl_3$) δ: 3.5, 7.4, 26.9, 121.8, 124.9, 125.9, 127.5, 128.5, 129.2, 135.6, 148.2, 162.3. IR (ATR): 2951 w, 2908 w, 2874 w. MS, *m/z* (CI, relative intensity, %): 258 ([M+H]$^+$, 100), 228 (8). HRMS Calcd for $C_{16}H_{24}NSi$ ([M+H]$^+$): 258.1678. Found: 258.1675.

7-Methoxy-1-[(triethylsilyl)methyl]-9*H*-pyrido[3,4-*b*]indole (2n).



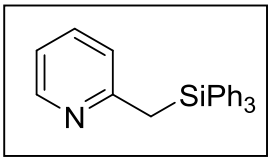
2n was obtained by flash column chromatography on silica-gel (R_f = 0.06 in hexane/EtOAc = 5/1) and subsequent filtration through a pad of NH_2-modified silica-gel (1.8 cm id × 5 cm h) using 120 mL of hexane as the eluent in 86% yield (140.4 mg) as a pale yellow solid. Mp = 106-108 ºC. ^{1}H NMR ($CDCl_3$) δ: 0.60 (q, *J* = 7.8 Hz, 6H), 0.89 (t, *J* = 7.8 Hz, 9H), 2.58 (s, 2H), 3.91 (s, 3H), 6.88 (dd, *J* = 8.7, 2.3 Hz, 1H), 6.96 (d, *J* = 2.3 Hz, 1H), 7.59 (d, *J* = 5.5 Hz, 1H), 7.93 (d, *J* = 8.7 Hz, 1H), 8.01 (br s, 1H), 8.26 (d, *J* = 5.5 Hz, 1H).^{13}C NMR ($CDCl_3$) δ: 4.0, 7.4, 21.2, 55.8, 94.9, 109.7, 110.7, 116.3, 122.7, 128.3, 133.9, 139.2, 141.5, 144.9, 160.7. IR (ATR): 3064 w, 2952 w, 2873 w, 1629 m. MS, *m/z* (CI, relative intensity, %): 327 ([M+H]$^+$, 100), 326 (11), 297(8), 213(7). HRMS Calcd for $C_{19}H_{27}N_2OSi$ ([M+H]$^+$): 327.1893. Found: 327.1889.

2-[(Triethylsilyl)methyl]thiazole (2o).



2o was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.26 in hexane/EtOAc = 50/1) in 53% yield (57.3 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.60 (q, *J* = 8.0 Hz, 6H), 0.94 (t, *J* = 8.0 Hz, 9H), 2.59 (s, 2H), 7.04 (d, *J* = 3.4 Hz, 1H), 7.57 (d, *J* = 3.4 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.2, 7.3, 20.2, 116.8, 142.1, 169.4. IR (ATR): 2952 w, 2909 w, 2875 w. MS, m/z (EI, relative intensity, %): 185 (17), 184 (100), 170 (12), 157 (14), 156 (36), 129 (20), 128 (22), 115 (11), 87 (70), 86 (21), 59 (45), 58 (17). HRMS Calcd for $C_{10}H_{19}NSSi$ (M^+): 213.1007. Found: 284.1009.

2-[(Triphenylsilyl)methyl]pyridine (3a).



3a was obtained by flash column chromatography on silica-gel (R_f = 0.19 in hexane/EtOAc = 10/1) and subsequent filtration through a pad of NH_2-modified silica-gel (1.8 cm id × 5 cm h) using 120 mL of hexane as the eluent in 54% yield (95.7 mg) as a white solid. Mp = 61-63 ºC. ^{1}H

NMR ($CDCl_3$) δ: 3.22 (s, 2H), 6.68 (d, *J* = 8.3 Hz, 1H), 6.93 (t, *J* = 6.2 Hz, 1H), 7.31-7.34 (m, 7H), 7.38-7.42 (m, 3H), 7.46 (dd, *J* = 6.6, 1.1 Hz, 6H), 8.35 (d, *J* = 4.6 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 27.1, 119.8, 123.4, 127.9, 129.7, 134.2, 135.8, 136.1, 149.0, 159.5. IR (ATR): 3066 w, 3042 w, 3013 w, 2925 w, 2853 w. MS, m/z (EI, relative intensity, %): 351 (M^+, 5), 350 (40), 275 (17), 274 (100), 259 (55), 181 (15). HRMS Calcd for $C_{24}H_{21}NSi$ ($[M+H]^+$): 351.1522. Found: 352.1525.

2.5 References and Notes

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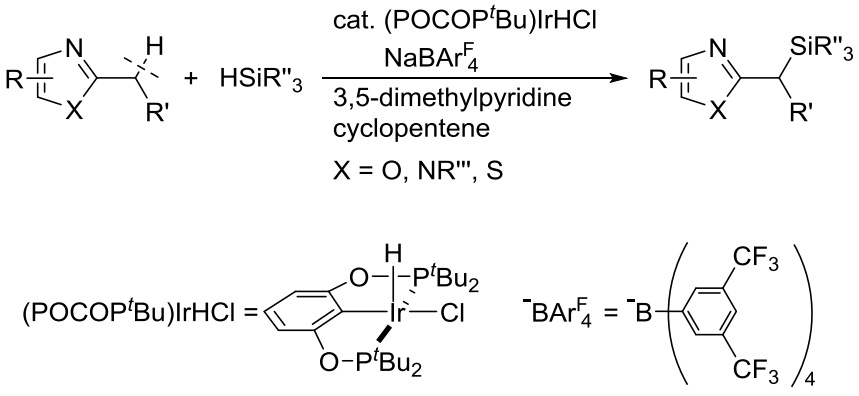
Chapter 3

The Cationic Iridium-Catalyzed C(sp^3)-H Silylation of 2-Alkyl-1,3-azoles at the α-Position in the 2-Alkyl Group Leading to 2-(1-Silylalkyl)-1,3-azoles

3.1 Introduction

As mentioned in Chapters 1 and 2, the author found that the $Ir_4(CO)_{12}$ complex is effective for the regioselective C(sp^3)-H silylation of alkylpyridines at the α-position in the C2- or C4-substituent, which appeared to proceed via the formation of a key intermediate, an electrophilic silicon species, formed by the reaction of $Ir_4(CO)_{12}$ with hydrosilanes, in the catalytic cycle. On the other hand, the reaction of 2-methyloxazole, which represents a class of 5-membered heterocyclic compounds, gave a complex mixture. The author's next focus was on the use of other complexes that have the ability to electrophilically activate a hydrosilane derivatives, and were examined in the regioselecitive α-C(sp^3)-H silylation of 2-alkyloxazoles and other 2-alkyl-1,3-azoles. Among the reported complexes that were examined, the author was pleased to find that Brookhart's complex, (POCOP^{t}Bu)IrHCl,[1] proved to be an ideal candidate. Chapter 3 described the (POCOP^{t}Bu)IrHCl/NaBAr$^F_4$-catalyzed regioselective C(sp^3)-H silylation of 2-alkyl-1,3-azoles at the α-position in a 2-alkyl group leading to the production of 2-(1-silylalkyl)-1,3-azole derivatives (Scheme 1).

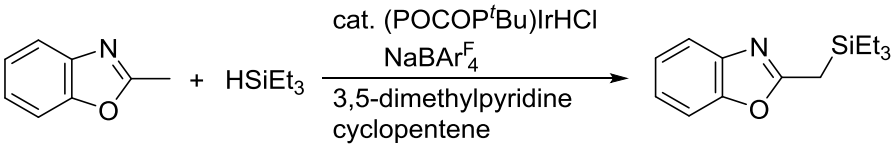
Scheme 1. (POCOP^{t}Bu)IrHCl/NaBAr$^F_4$-Catalyzed Regioselective C(sp^3)-H Silylation of 2-Alkyl-1,3-azoles with Hydrosilanes



3.2 Results and Discussion

Table 1 shows the results for the reaction of 2-methylbenzoxazaole (**1a**) with triethylsilane under optimized reaction conditions with (POCOP^{t}Bu)IrHCl and NaBAr$^F_4$ as a catalyst system, and under several different sets of reaction conditions. When 3,5-dimethylpyridine and cyclopentene, the latter of which acted as a hydrogen acceptor, were added to the reaction mixture, the silylated compound **2a** was produced in 98% yield, as determined from the ^{1}H NMR spectrum, and was isolated in 90% yield by silica-gel column chromatography (entry 1). The results cited in entries 2 and 3 indicate that a cationic iridium complex generated in situ is the actual active species for the reaction.

Table 1. Optimization of the Reaction Conditions[a]



1a **2a**

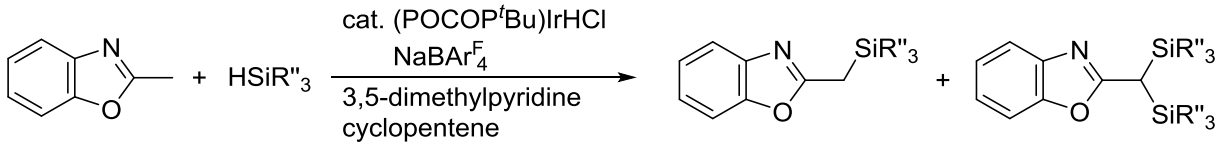
entry	deviation from the standard reaction conditions	yields (%)[b]	
		2a	**1a**
1	None	98 (90)[c]	0
2	NaB(C_6F_5)$_4$ instead of NaBAr$^F_4$	89	8
3	without NaBAr$^F_4$	0	90
4	without 3,5-dimethylpyridine	0	67
5	without cyclopentane	61	20
6	cyclohexene instead of cyclopentene	93	7
7	^{t}BuCH=CH_2 instead of cyclopentene	83	0
8	norbornene instead of cyclopentene	20	67
9	at 60 °C	4	94
10	$Ir_4(CO)_{12}$[d,e]	0	81
11	Cp*IrCl[η^2-2-(2-Py)Ph]/NaBAr$^F_4$[d]	trace	75
12	B(C_6F_5)$_3$[d]	0	99
13	$FeCl_2$/NaBAr$^F_4$[d]	0	98
14	Zn(OTf)$_2$	0	99
15	(POCOP^{t}Bu)RhHCl/NaBAr$^F_4$[d]	trace	81

[a]Reaction conditions: **1a** (0.3 mmol), HSiEt$_3$ (1.2 mmol), (POCOP^{t}Bu)IrHCl (0.0075 mmol), NaBAr$^F_4$ (0.0075 mmol), 3,5-dimethylpyridine (0.06 mmol), and cyclopentene (0.6 mmol) at 80 ºC for 20 h under N_2. [b]Yields of **2a** and **2a'** were determined from ^{1}H NMR spectra with 1,3-dihydro-2-benzofuran as an internal standard. The yield of the unreacted **1a** was determined from the GC spectrum with tridecane as an internal standard. [c]The number shown in parentheses is the isolated yield. [d]The complex was used as a catalyst instead of (POCOP^{t}Bu)IrHCl/NaBAr$^F_4$. [e]$Ir_4(CO)_{12}$ (0.0019 mmol)

The addition of 3,5-dimethylpyridine was necessary for the reaction to proceed (entry 4). The fact that the reaction occurred, even in the absence of cyclopentene, indicates that the hydrogen atoms at the α-position and that on the silicon atom were released in the form of H_2 (entry 5). Nonetheless, the addition of other hydrogen acceptors, such as cyclohexene and *tert*-butylethylene, also resulted in better product yields, compared to the case in which they were not present (entries 6 and 7). However, in the presence of norbornene, the reaction was retarded (entry 8). $Ir_4(CO)_{12}$ was not an effective catalyst in this reaction (entry 10). Other complexes, such as Cp*IrCl[η^2-2-(2-Py)Ph]/$NaBAr^F_4$,[2] $B(C_6F_5)_3$,[3] $FeCl_2/NaBAr^F_4$,[4] and $Zn(OTf)_2$,[5] did not catalyze the reaction, although they are also known to activate hydrosilanes in a manner similar to the (POCOP^{t}Bu)IrHCl/$NaBAr^F_4$ catalyst. When the iridium in the catalyst was replaced with rhodium, only trace amounts of **2a** were produced (entry 15).

Some other hydrosilanes were also examined in the reaction of **1a** (Scheme 2). Although other trialkylsilanes such as $HSiEt_2Me$ and $HSiEtMe_2$ were found to be applicable to the present reaction, the final reaction was comprised of mixtures of monosilylated products (**3a** and **4a**) and disilylated products (**3a'** and **4a'**). However, proper tuning of the reaction conditions in the reaction with $HSiEt_2Me$, by decreasing the amount of $HSiEt_2Me$ to 0.6 mmol, using $NaB(C_6F_5)_4$ and cyclohexene instead of $NaBAr^F_4$ and cyclopentene, respectively, and at a lower reaction temperature of 60 ºC, permitted the monosilylated product **3a** to be selectively produced in 87% yield (Scheme 3). On the other hand, the reactions with $HSiPhMe_2$ and $HSi(OSiMe_3)Me_2$ gave complex reaction mixtures containing only small amounts of the desired products.

Scheme 2. Screening of hydrosilanes[a]

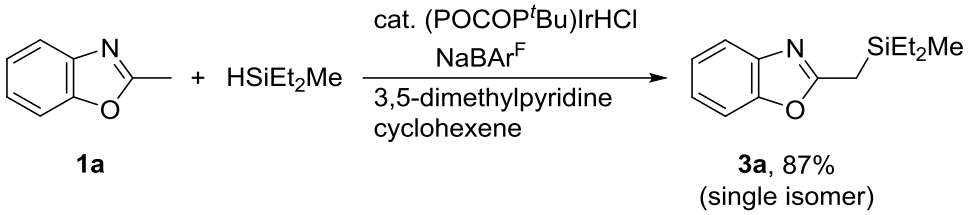


1a **2a-4a** **2a'-4a'**

$HSiEt_3$	98% (**2a**)	0%
$HSiEt_2Me$	21% (**3a**)	72% (**3a'**)
$HSiEtMe_2$	17% (**4a**)	73% (**4a'**)

[a]Reaction conditions: **1a** (0.3 mmol), hydrosilane (1.2 mmol), (POCOP^{t}Bu)IrHCl (0.0075 mmol), $NaBAr^F_4$ (0.0075 mmol), 3,5-dimethylpyridine (0.06 mmol), and cyclopentene (0.6 mmol) at 80 ºC for 20 h under N_2. Yields of products were determined from ^{1}H NMR spectra with 1,3-dihydro-2-benzofuran as an internal standard.

Scheme 3. Tuning the Reaction Conditions When Using $HSiEt_2Me$[a]

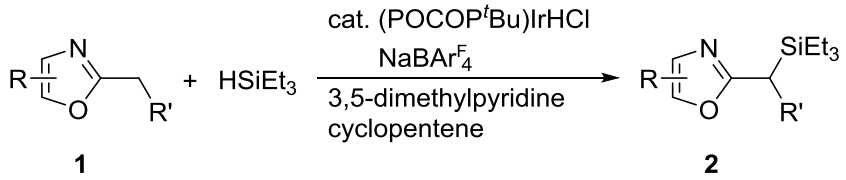


[a]Reaction conditions: **1a** (0.3 mmol), $HSiEt_2Me$ (0.6 mmol), (POCOP^{t}Bu)IrHCl (0.0075 mmol), $NaB(C_6F_5)_4$ (0.0075 mmol), 3,5-dimethylpyridine (0.06 mmol), and cyclohexene (0.6 mmol) at 60 ºC for 20 h under N_2. Yields of products were determined from ^{1}H NMR spectra with 1,3-dihydro-2-benzofuran as an internal standard.

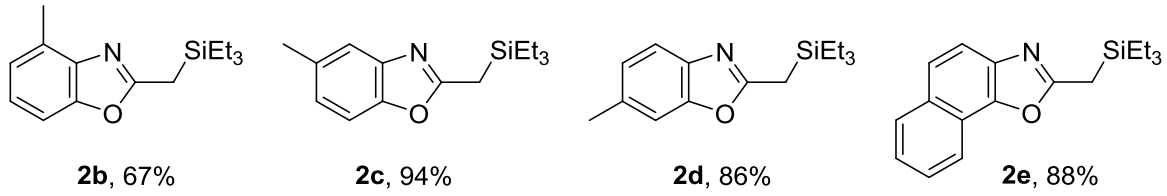
A number of 2-alkyl-1,3-azoles were examined under the optimized reaction conditions (Table 2). None of the methyl groups on the phenyl ring in 2-methylbenzoxazole participated in the silylation and **2b**-**2d** were produced, in good yields, expect for **2b**. Whereas the naphthalene-fused oxazole derivatives **1e** and **1f** reacted under the reaction conditions to give **2e** and **2f** in 88% and 80% yields, respectively, the reaction of the [1,2-*d*]-fused oxazole **1g** resulted in the complete recovery of the starting material at 80 ºC, and, gave **2g** in 31% yield even at the elevated reaction temperature of 160 ºC. The reaction of the ethyl-substituted benzoxazole **1h** took place regioselectively at the α-position in the butyl group to produce **2h** in 81%. However, no reaction occurred when 2-isopropylbenzoxazole was used as the substrate. Functional groups, such as methoxy (**2i**), bromo (**2k**), chloro (**2k**), and methoxycarbonyl (**2l**) groups, were all tolerated in the reaction. Although the reaction of 2-methyloxazole gave a complex reaction mixture, probably due to instability of the starting material and/or the desired product, 2,4-dimethyloxazole could be converted into **2m** in 52% yield. To my delight, 1,2-dimethylbenzimidazole (**1n**) and thiazole derivatives (**1o**-**1p**) were also applicable to the present reaction, giving **2n**-**2p**.

A plausible mechanism for the regioselective silylation of 2-alkyl-1,3-azoles in the absence of a hydrogen acceptor, which would be simpler than that in the presence of an acceptor, is shown in Scheme 4. A cationic iridium species **I** is formed by the in situ reaction of (POCOP^{t}Bu)IrHCl with $NaBAr^F_4$. A hydrosilane is next activated by **I** via the formation of an η^1-hydrosilane complex **II**.[6] The silyl group in **II** is abstracted by the added pyridine derivative to form a silylpyridinium species **III** and a dihydridoiridium complex **IV**,[7] from the latter of which, the reductive elimination of H_2 occurs to form **V**. The coordination of the pyridine derivative to the

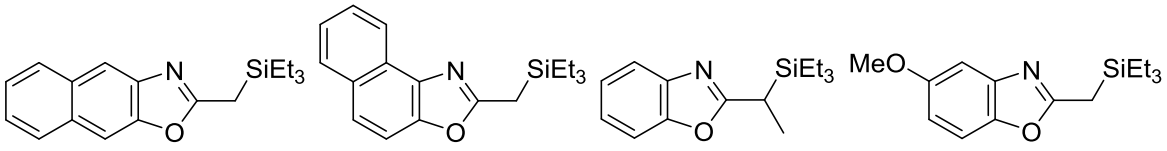
Table 2. Scope of Substrates[a]



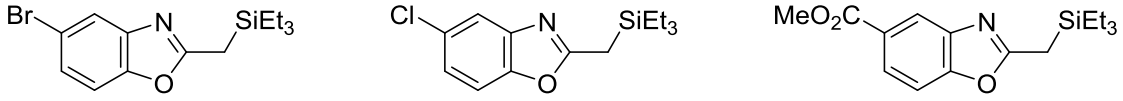
1 **2**



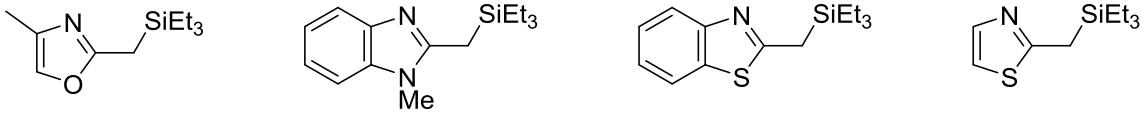
2b, 67% **2c**, 94% **2d**, 86% **2e**, 88%



2f, 80% **2g**, 34%[e] **2h**, 81%[b] **2i**, 88%



2j, 84% **2k**, 89%[b] **2l**, 58%[c]

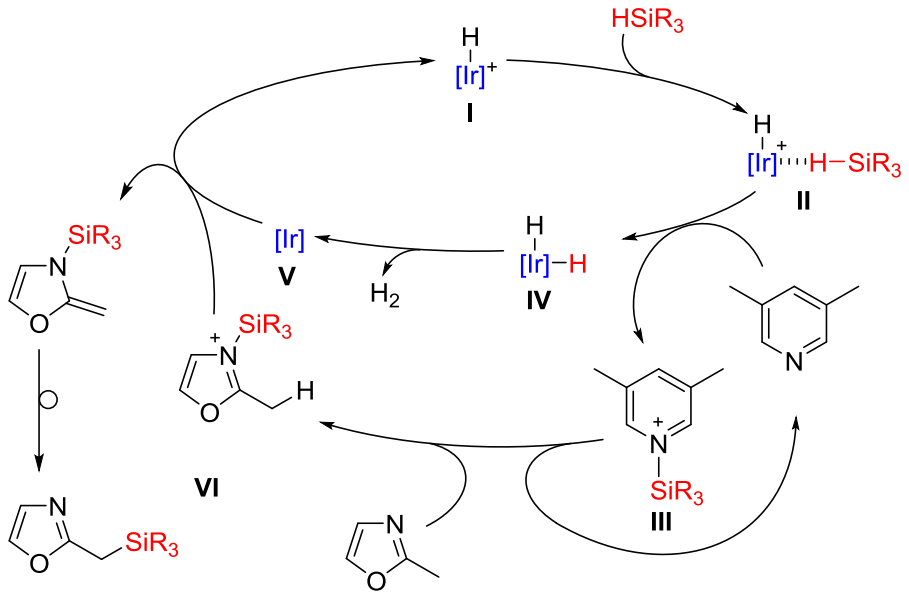


2m, 52%[d] **2n**, 52%[e] **2o**, 85%[b] **2p**, 82%[d]

[a]Reaction conditions: **1** (0.3 mmol), $HSiEt_3$ (1.2 mmol), (POCOP^{t}Bu)IrHCl (0.0075 mmol), $NaBAr^F_4$ (0.0075 mmol), 3,5-dimethylpyridine (0.06 mmol), and cyclopentene (0.6 mmol) at 80 ºC for 20 h under N_2. Isolated yields are given. [b]At 100 ºC. [c]At 120 ºC. [d]At 130 ºC. [e]At 160 ºC.

iridium center in **IV** might accelerate the elimination of H_2, as was reported for the generation of H_2 from **IV**, which proceeded smoothly under an atmosphere of CO.[8] The transfer of the silyl group from **III** to the 2-alkyl-1,3-azole substrate occurs to form an *N*-silylazolinium species **VI**.[9] The subsequent deprotonation of **VI** by **V** then affords a 2-methylene-*N*-silyl-2,3-dihydroazole, with regeneration of **I**. Finally, the migration of the silyl group on the nitrogen atom to the methylene carbon atom produces the desired product. The reason for the low product yields in the reactions of **1b** and **1g** can be attributed to steric factors in case of the formation of **VI**.

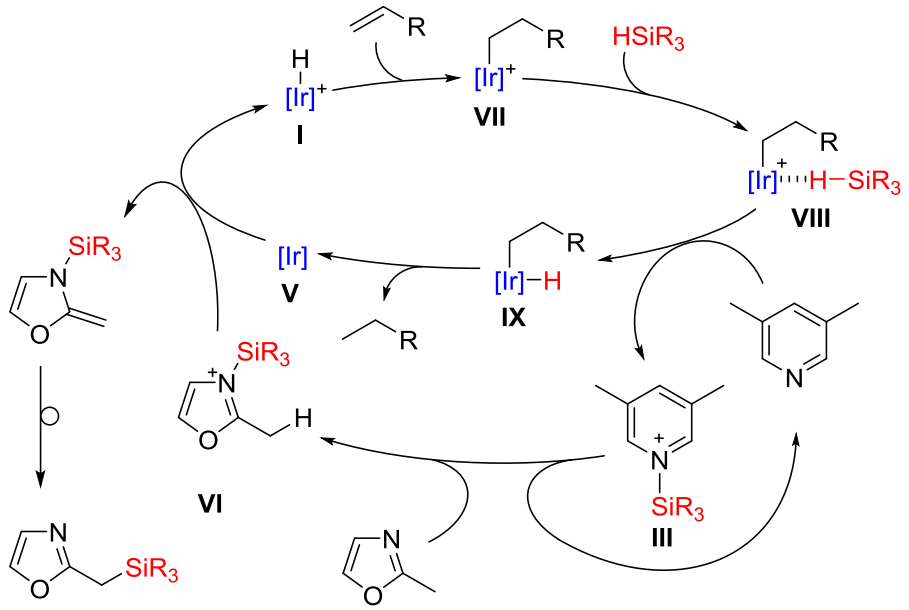
Scheme 4. A Plausible Reaction Mechanism in the Absence of a Hydrogen Acceptor



In the case of the silylation in the presence of a hydrogen acceptor, the hydrogen atoms at the α-position in the substrate and that on the silicon atom are removed from the reaction via the formation of alkane. One possibility involves the hydrogen atoms being trapped via the hydrogenation of the acceptor with the dihydridoiridium complex **IV**, as shown in Scheme 4. As shown in Table 1, the presence of added norbornene resulted in a lower product yield than that with other alkenes, even in its absence. Although the author has no information regarding the reactivity of **IV** toward norbornene, it is difficult to conclude that hydrogenation of norbornene with **IV** under the present reaction conditions would not occur. Another possibility is that the hydrogen acceptor participates in an earlier stage of the reaction, prior to the formation of **V**. Given these considerations, a proposed reaction mechanism for the reaction under the above conditions is shown in Scheme 5. First, the monohydridoiridium complex **I** reacts with the hydrogen acceptor to afford an alkyl complex **VII**, which activates the hydrosilane via the formation of **VIII**. Hartwig and a co-worker proposed a reaction mechanism in which two hydrogen atoms are trapped by the acceptor alkene starting from the insertion of the alkene into the Rh-H bond in the monohydridorhodium complex, and not the dihydridorhodium complex.[10] Bulkier substituents on the silicon atom and the hydrogen acceptor would make the formation of **VIII** more difficult, due to steric repulsion, thus leading to a lower reaction rate. The abstraction of the silyl group from **VIII** by the added pyridine occurs to form **III** and the complex **IX**. The subsequent reductive elimination of an alkane from **IX** gives **V**. The remaining reaction path

from **III** to the final product and the regeneration of **I** is the same as that shown in Scheme 4. However, the possibility that the mechanism involves the hydrogenation of the acceptor with **IV** cannot be completely ruled out at the present time.

Scheme 5. A Plausible Reaction Mechanism in the Presence of a Hydrogen Acceptor



3.3 Conclusion

The author demonstrated that a cationic iridium complex, formed by the reaction of (POCOP^{t}Bu)IrHCl with NaBAr$^F{}_4$, catalyze the regioselective C(sp^3)-H silylation of 2-alkyl-1,3-azoles to produce 2-(1-silylalkyl)-1,3-azoles. Although the reaction proceeded both in the presence and absence of a hydrogen acceptor, the presence of an added acceptor gave better results, in terms of the efficiency of the reaction. The proposed reaction mechanism involves the formation of an electrophilic silicon species as a key intermediate

3.4 Experimental Section

General Information.

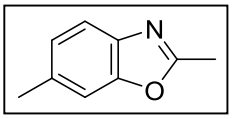
^{1}H and ^{13}C NMR spectra were recorded on 400 and 100 MHz spectrometers, respectively, using $CDCl_3$ and acetone-d_6 as solvents. Data were recorded as follows: chemical shifts in ppm (δ), multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, c = complex), coupling constants (Hz), and integration. Infrared spectra (IR) were recorded by an ATR technique. Absorption data were reported in reciprocal centimeters with the following relative intensities: s (strong), m (medium), or w (weak). Mass spectra were obtained using a spectrometer with a

quadrupole mass analyzer at 70 eV. High-resolution mass spectra (HRMS) were obtained using a spectrometer with a double-focusing mass analyzer. Analytical gas chromatography (GC) was carried out on a chromatograph equipped with a flame ionization detector. Melting points were determined on a capillary point apparatus equipped with a digital thermometer and were uncorrected.

Materials.

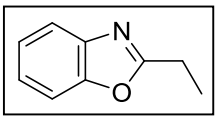
1b, **1e-g**, **1j-k**, **1m-n**, and **1p** were purchased and were used as received. Other organic compounds, except **1d**, **1h**, **1l**, and 2-isopropylbenzo[*d*]oxazole were purchased from commercial sources and distilled over CaH_2 before use. Compounds **1d**, **1h**, **1l**, and 2-isopropylbenzo[*d*]oxazole were prepared as described below. Complexes (POCOP^{t}Bu)IrHCl,[11] (POCOP^{t}Bu)RhHCl,[12] $NaBAr^F{}_4$,[13] and $NaB(C_6F_5)_4$[14] were prepared by following the procedure described in the literature. Other metal complexes were purchased from commercial sources and used without further purification.

2,6-Dimethylbenzo[*d*]oxazole (1d).[15]



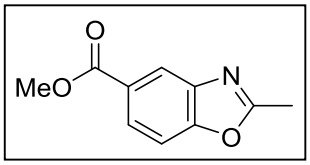
The procedure reported by Hartwig[16] was modified by using 2-amino-5-methylphenol (1.00 g, 8.12 mmol) in place of 2-amino-4-methoxy-phenol to produce **1d**, which was isolated by distillation under reduced pressure (42 °C/52 mmHg) in 74% yield (0.88 g, 5.98 mmol) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 2.42 (s, 3H), 2.57 (s, 3H), 7.06 (m, 1H), 7.22 (d, J = 1.0 Hz, 1H), 7.49 (d, J = 8.2 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 14.4, 21.5, 110.3, 118.6, 125.1, 134.5, 139.2, 151.1, 163.0.

2-Ethylbenzo[*d*]oxazole (1h).[17]



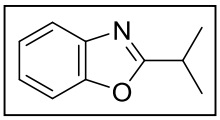
The procedure reported by Hartwig[16] was modified by using 2-aminophenol (1.50 g, 13.7 mmol) and 1,1,1-trimethoxy-propane (1.89 g, 13.7 mmol) in place of 2-amino-4-methoxyphenol and trimethyl orthoacetate, respectively, to produce **1h**, which was isolated by distillation under reduced pressure (61 °C/84 mmHg) in 74% yield (1.49 g, 10.1 mmol) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 1.44 (t, J = 7.6 Hz, 3H), 2.94 (q, J = 7.6 Hz, 2H), 7.27 (tt, J = 5.5, 1.9 Hz, 2H), 7.44-7.46 (m, 1H), 7.65-7.68 (m, 1H). ^{13}C NMR ($CDCl_3$) δ: 10.9, 22.2, 110.2, 119.5, 124.0, 124.4, 141.4, 150.8, 168.1.

Methyl 2-methylbenzo[*d*]oxazole-5-carboxylate (1l).[18]



The procedure reported by Hartwig[16] was modified by using methyl 3-amino-4-hydroxybenzoate[19] (0.61g, 3.65 mmol), in place of 2-amino-4-methoxyphenol to produce **1l**, which was isolated by flash column chromatography on silica-gel (R_f = 0.09 in hexane/EtOAc = 10/1) in 68% yield (52.6 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 2.68 (s, 3H), 3.95 (s, 3H), 7.51 (d, *J* = 8.6 Hz, 1H), 8.06 (dd, *J* = 8.6, 1.6 Hz, 1H), 8.34 (s, 1H). ^{13}C NMR (actetone-d_6) δ: 14.3, 52.5, 110.1, 121.5, 127.0, 127.4, 142.7, 154.7, 166.4, 166.8.

2-Isopropylbenzo[*d*]oxazole.[20]

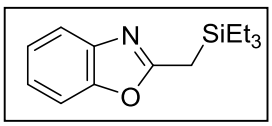


The procedure reported by Hartwig[15] was modified by using 2-aminophenol (0.87 g, 7.98 mmol) and 1,1,1-trimethoxy-2-methylpropane (1.19 g, 8.03 mmol) in place of 2-amino-4-methoxyphenol and trimethyl orthoacetate, respectively, to produce 2-isopropylbenzo[*d*]oxazole, which was isolated by distillation under reduced pressure (68 °C/54 mmHg) in 70% yield (0.90 g, 5.58 mmol) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 1.45 (d, *J* = 7.1 Hz, 6H), 3.19-3.27 (m, 1H), 7.27 (t, *J* = 3.7 Hz, 2H), 7.46 (dd, *J* = 7.3, 3.7 Hz, 1H), 7.67-7.69 (m, 1H). ^{13}C NMR ($CDCl_3$) δ: 20.4, 28.9, 110.3, 119.7, 124.0, 124.4, 141.3, 150.7, 171.3.

Typical Procedure for the (POCOP^{t}Bu)IrHCl/NaBAr$^F_4$-Catalyzed C−H Silylation of 2-Alkyl- 1,3-azoles with Hydrosilanes.

An 8 mL Schlenk tube was flame-dried and purged with N_2. After the tube was cooled to room temperature, (POCOP^{t}Bu)IrHCl (4.7 mg, 7.5 x 10^{-3} mmol), NaBAr$^F_4$ (6.6 mg, 7.5 x 10^{-3} mmol), 3,5-dimethylpyridine (6.4 mg, 0.06 mmol), **1** (0.3 mmol), cyclopentene (40.8 mg, 0.6 mmol), and hydrosilane (1.2 mmol) were placed in the Schlenk tube. The reaction mixture was stirred at 80 °C for 20 h. After cooling the mixture to room temperature, the volatiles were removed in vacuo. The product was isolated by flash column chromatography on NH_2-modified silica gel.

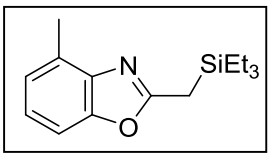
2-[(Triethylsilyl)methyl]benzo[*d*]oxazole (2a).



2a was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.17 in hexane/EtOAc = 40/1) in 90% yield (66.8 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.54 (q, *J* = 7.8 Hz, 6H), 0.96 (t, *J* =

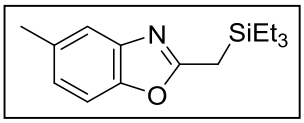
7.8 Hz, 9H), 2.42 (s, 2H), 7.20-7.28 (m, 2H), 7.41-7.44 (m, 1H), 7.59-7.61 (m, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.5, 7.2, 15.0, 109.9, 118.9, 123.6, 123.9, 142.2, 150.9, 167.4. IR (ATR): 2953 w, 2876 w. MS, *m/z* (EI, relative intensity, %): 247 (M^+, 4), 246 (12), 219 (17), 218 (100), 191 (11), 190 (62), 162 (16), 87 (67), 86 (19), 59 (35). HRMS Calcd for $C_{14}H_{21}NOSi$ (M^+): 247.1392; found: 247.1396.

4-Methyl-2-[(triethylsilyl)methyl]benzo[*d*]oxazole (2b).



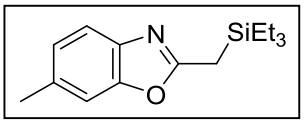
2b was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.21 in hexane/EtOAc = 40/1) in 67% yield (52.6 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.65 (q, *J* = 8.1 Hz, 6H), 0.96 (t, *J* = 8.1 Hz, 9H), 2.43 (s, 2H), 2.57 (s, 3H), 7.04 (d, *J* = 7.3 Hz, 1H), 7.10 (d, *J* = 7.8 Hz, 1H), 7.24 (d, *J* = 8.7 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.6, 7.2, 15.1, 16.7, 107.3, 123.2, 124.5, 129.2, 141.2, 150.6, 166.6. IR (ATR): 2953 w, 2876 w. MS, *m/z* (EI, relative intensity, %): 261 (M^+, 16), 246 (21), 233 (20), 232 (100), 204 (27), 115 (23), 88 (12), 87 (97), 86 (20), 59 (41). HRMS Calcd for $C_{15}H_{24}NOSi$ ($[M+H]^+$): 262.1627; found: 262.1624.

5-Methyl-2-[(triethylsilyl)methyl]benzo[*d*]oxazole (2c).



2c was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.26 in hexane/ EtOAc = 40/1) in 94% yield (72.2 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.64 (q, *J* = 8.0 Hz, 6H), 0.95 (t, *J* = 8.0 Hz, 9H), 2.40 (s, 2H), 2.44 (s, 3H), 7.02 (d, *J* = 8.3 Hz, 1H), 7.27 (d, *J* = 8.3 Hz, 1H), 7.38 (s, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.6, 7.2, 15.1, 21.5, 109.3, 119.0, 124.6, 133.6, 142.4, 149.1, 167.5. IR (ATR): 2953 w, 2876 w. MS, *m/z* (EI, relative intensity, %): 261 (M^+, 6), 233 (17), 232 (100), 205 (11), 204 (59), 177 (11), 176 (14), 87 (57), 86 (14), 59 (31). HRMS Calcd for $C_{15}H_{23}NOSi$ (M^+): 261.1549; found: 261.1549.

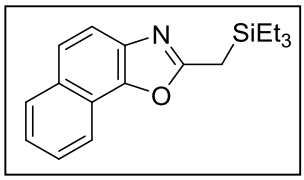
6-Methyl-2-[(triethylsilyl)methyl]benzo[*d*]oxazole (2d).



2d was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.19 in hexane/ EtOAc = 40/1) in 86% yield (67.5 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.63 (q, *J* = 8.0 Hz, 6H), 0.95 (t, *J* = 8.0 Hz, 9H), 2.38 (s, 2H), 2.44 (s, 3H), 7.05 (d, *J* = 8.2 Hz, 1H), 7.22 (s, 1H), 7.45 (d, *J* = 8.2 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.5, 7.2, 14.9, 21.7, 110.2, 118.2, 124.9, 133.8, 139.9, 151.1,

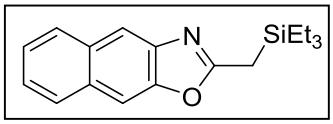
166.7. IR (ATR): 2953 w, 2876 w. MS, *m/z* (EI, relative intensity, %): 261 (M^+, 16), 260 (17), 233 (22), 232 (100), 205 (16), 204 (58), 177 (16), 176 (19), 87 (50), 86 (16), 59 (28). HRMS Calcd for $C_{15}H_{24}NOSi$ ($[M+H]^+$): 262.1627; found: 262.1627.

2-[(Triethylsilyl)methyl]naphtho[2,1-*d*]oxazole (2e).



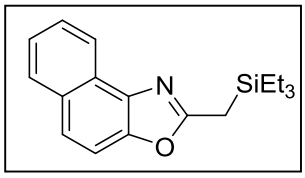
2e was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.20 in hexane/ EtOAc = 40/1) in 88% yield (78.5 mg) as a colorless oil. ^1H NMR ($CDCl_3$) δ: 0.67 (q, *J* = 8.0 Hz, 6H), 0.98 (t, *J* = 8.0 Hz, 9H), 2.52 (s, 2H), 7.44 (t, *J* = 7.6 Hz, 1H), 7.56 (t, *J* = 7.3 Hz, 1H), 7.68 (d, *J* = 8.7 Hz, 1H), 7.71 (d, *J* = 8.7 Hz, 1H), 7.91 (d, *J* = 7.8 Hz, 1H), 8.13 (d, *J* = 8.2 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.5, 7.2, 15.1, 118.3, 119.8, 120.2, 124.5, 124.9, 126.6, 128.6, 131.0, 138.4, 146.2, 166.5. IR (ATR): 2953 w, 2875 w. MS, *m/z* (EI, relative intensity, %): 297 (M^+, 34), 296 (20), 269 (27), 268 (100), 241 (14), 240 (44), 214 (13), 213 (16), 212 (19), 115 (10), 87 (49), 86 (15), 59 (35). HRMS Calcd for $C_{18}H_{24}NOSi$ ($[M+H]^+$): 298.1627; found: 298.1623.

2-[(Triethylsilyl)methyl]naphtho[2,3-*d*]oxazole (2f).



2f was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.18 in hexane/ EtOAc = 40/1) in 80% yield (71.4 mg) as a colorless oil. ^1H NMR ($CDCl_3$) δ: 0.67 (q, *J* = 7.9 Hz, 6H), 0.97 (t, *J* = 7.9 Hz, 9H), 2.48 (s, 2H), 7.41-7.48 (m, 2H), 7.80 (s, 1H), 7.89-7.92 (m, 1H), 7.93-7.96 (m, 1H), 8.00 (s, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.6, 7.2, 15.6, 105.6, 115.7, 124.5, 125.0, 127.9, 128.4, 131.0, 131.3, 142.3, 150.0, 170.0. IR (ATR): 2953 w, 2875 w. MS, *m/z* (EI, relative intensity, %): 297 (M^+, 33), 296 (17), 269 (26), 268 (100), 241 (16), 240 (59), 213 (15), 212 (18), 210 (16), 183 (17), 115 (13), 114 (13), 87 (45), 86 (15), 59 (29). HRMS Calcd for $C_{18}H_{24}NOSi$ ($[M+H]^+$): 298.1627; found: 298.1628.

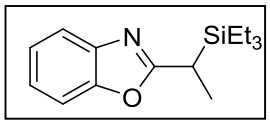
2-[(Triethylsilyl)methyl]naphtho[1,2-*d*]oxazole (2g).



2g was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.21 in hexane/ EtOAc = 40/1) in 34% yield (30.3 mg) as a colorless oil. ^1H NMR ($CDCl_3$) δ: 0.67 (q, *J* = 7.9 Hz, 6H), 0.97 (t, *J* = 7.9 Hz, 9H), 2.53 (s, 2H), 7.48 (ddd, *J* = 8.2, 6.9, 0.9 Hz, 1H),

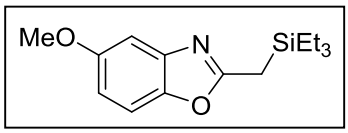
7.59 (d, J = 8.9 Hz, 1H), 7.60 (ddd, J = 8.2, 6.9, 0.9 Hz, 1H), 7.68 (d, J = 8.7 Hz, 1H), 7.92 (d, J = 8.2 Hz, 1H), 8.45 (d, J = 8.2 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.7, 7.2, 15.2, 110.6, 122.2, 124.3, 125.0, 126.1, 126.6, 128.5, 131.0, 137.2, 147.9, 166.5. IR (ATR): 2952 w, 2875 w. MS, *m/z* (EI, relative intensity, %): 298 (M^+, 16), 297 (65), 296 (71), 282 (34), 281 (50), 269 (19), 268 (79), 267 (24), 240 (16), 212 (11), 210 (14), 166 (14), 115 (23), 106 (14), 88 (11), 87 (100), 86 (25), 59 (52). HRMS Calcd for $C_{18}H_{24}NOSi$ ($[M+H]^+$): 298.1627; found: 298.1627.

2-[1-(Triethylsilyl)ethyl]benzo[*d*]oxazole (2h).



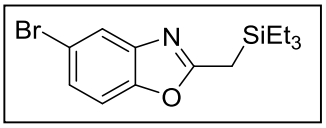
2h was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.26 in hexane/EtOAc = 40/1) in 81% yield (63.5 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.65 (q, J = 7.9 Hz, 6H), 0.94 (t, J = 7.9 Hz, 9H), 1.53 (d, J = 7.4 Hz, 3H), 2.70 (q, J = 7.4 Hz, 1H), 7.20-7.27 (m, 2H), 7.43 (d, J = 7.5 Hz, 1H), 7.62 (d, J = 7.5 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 2.5, 7.3, 12.6, 21.5, 109.9, 119.0, 123.6, 123.9, 142.0, 150.6, 171.5. IR (ATR): 2954 w, 2876 w. MS, *m/z* (EI, relative intensity, %): 261 (M^+, 7), 260 (22), 233 (22), 232 (100), 205 (13), 204 (47), 177 (10), 115 (16), 87 (80), 86 (18), 59 (36). HRMS Calcd for $C_{15}H_{24}NOSi$ ($[M+H]^+$): 262.1627; found: 262.1629.

5-Methoxy-2-[(triethylsilyl)methyl]benzo[*d*]oxazole (2i).



2i was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.09 in hexane/ EtOAc = 40/1) in 88% yield (73.2 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.64 (q, J = 7.8 Hz, 6H), 0.96 (t, J = 7.8 Hz, 9H), 2.39 (s, 2H), 3.83 (s, 3H), 6.81 (dd, J = 8.7, 2.5 Hz, 1H), 7.11 (d, J = 2.5 Hz, 1H), 7.28-7.31 (m, 1H).^{13}C NMR ($CDCl_3$) δ: 3.5, 7.2, 15.1, 56.0, 102.5, 109.9, 111.6, 143.0, 145.5, 157.0, 168.3. IR (ATR): 2953 w, 2876 w. MS, *m/z* (EI, relative intensity, %): 277 (M^+, 19), 276 (10), 249 (21), 248 (100), 221 (14), 220 (59), 207 (11), 193 (14), 192 (19), 87 (51), 86 (15), 59 (32). HRMS Calcd for $C_{15}H_{23}NO_2Si$ (M^+): 277.1498; found: 277.1498.

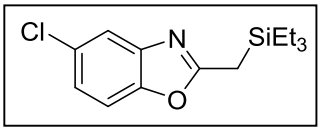
5-Bromo-2-[(triethylsilyl)methyl]benzo[*d*]oxazole (2j).



2j was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.20 in hexane/ EtOAc = 40/1) in 84% yield (82.2 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.63 (q, J = 7.9 Hz, 6H), 0.95 (t, J = 7.9 Hz, 9H), 2.41 (s, 2H), 7.28 (d, J = 8.4 Hz, 1H), 7.33 (dd, J = 8.4, 1.8 Hz, 1H),

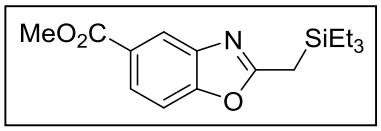
7.72 (d, J = 1.8 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.6, 7.2, 15.2, 111.1, 116.7, 121.9, 126.6, 143.8, 149.9, 168.9. IR (ATR): 2953 w, 2876 w. MS, *m/z* (EI, relative intensity, %): 326 (M^+[^{81}Br], 12), 324 (M^+[^{79}Br], 11), 299 (15), 298 (75), 297 (15), 296 (73), 270 (39), 268 (39), 242 (12), 240 (10), 115 (33), 114 (10), 88 (10), 87 (100), 86 (30) , 59 (39), 58 (10). HRMS Calcd for $C_{14}H_{21}{}^{81}BrNOSi$ ($[M+H]^+$): 326.0576; found: 326.0574.

5-Chloro-2-[(triethylsilyl)methyl]benzo[*d*]oxazole (2k).



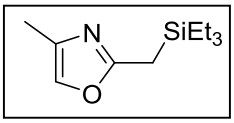
2k was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.24 in hexane/ EtOAc = 40/1) in 89% yield (75.3 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.64 (q, J = 8.0 Hz, 6H), 0.95 (t, J = 8.0 Hz, 9H), 2.41 (s, 2H), 7.18 (dd, J = 8.5, 2.1 Hz, 1H), 7.32 (d, J = 8.5 Hz, 1H), 7.57 (d, J = 2.1 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.5, 7.1, 15.2, 110.5, 118.9, 123.8, 129.3, 143.3, 149.4, 169.0. IR (ATR): 2954 w, 2876 w. MS, *m/z* (EI, relative intensity, %): 283 (M^+[^{37}Cl], 5), 283 (M^+[^{35}Cl], 1), 280 (11), 254 (29), 253 (16), 252 (81), 226 (17), 225 (10), 224 (49), 196 (11), 115 (28), 87 (100), 86 (28), 59 (41). HRMS Calcd for $C_{14}H_{21}{}^{37}ClNOSi$ $[M+H]^+$: 282.1081; found: 282.1084.

Methyl 2-[(triethylsilyl)methyl[benzo[*d*]oxazole-5-carboxylate (2l).



2l was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.17 in hexane/EtOAc = 40/1) in 58% yield (53.1 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.65 (q, J = 8.0 Hz, 6H), 0.96 (t, J = 8.0 Hz, 9H), 2.45 (s, 2H), 3.94 (s, 3H), 7.45 (d, J = 8.6 Hz, 1H), 8.00 (dd, J = 8.6, 1.7 Hz, 1H), 8.28 (d, J = 1.7 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.5, 7.2, 15.2, 52.4, 109.7, 120.8, 125.9, 126.4, 142.2, 153.8, 167.1, 168.9. IR (ATR): 2953 w, 2877 w, 1722 m, 1287 m. MS, *m/z* (EI, relative intensity, %): 277 (M^+, 21), 276 (100), 249 (12), 248 (56), 220 (11), 160 (14), 159 (18), 115 (15), 87 (62), 86 (15), 59 (31). HRMS Calcd for $C_{16}H_{24}NO_3Si$ ($[M+H]^+$): 306.1525; found: 306.1523.

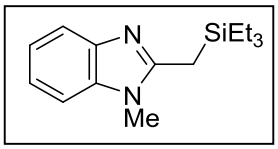
4-Methyl-2-[(triethylsilyl)methyl]oxazole (2m).



2m was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.14 in hexane/EtOAc = 40/1) in 52% yield (30.9 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.58 (q, J = 8.0 Hz, 6H), 0.94 (t, J = 8.0

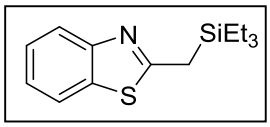
Hz, 9H), 2.10 (s, 3H), 2.20 (s, 2H), 7.18 (c, 1H).^{13}C NMR ($CDCl_3$) δ: 3.5, 7.1, 11.7, 14.2, 133.0, 136.1, 164.3. IR (ATR): 2952 w, 2876 w. MS, *m/z* (EI, relative intensity, %): 182 (85), 154 (47), 126 (19), 115 (11), 87 (100), 86 (17), 59 (47). HRMS Calcd for $C_{11}H_{21}NOSi$ (M^+): 211.1392; found: 211.1391.

1-Methyl-2-[(triethylsilyl)methyl]-1*H*-benzo[*d*]imidazole (2n).



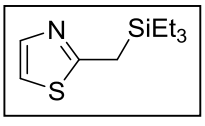
2n was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.11 in hexane/EtOAc = 1/1) in 52% yield (41.0 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.64 (q, *J* = 7.9 Hz, 6H), 0.93 (t, *J* = 7.9 Hz, 9H), 2.38 (s, 2H), 3.67 (s, 3H), 7.17-7.24 (c, 3H), 7.63-7.67 (c, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.7, 7.3, 13.6, 30.2, 108.6, 118.5, 121.2, 121.6, 135.8, 143.2, 155.2. IR (ATR): 2951 w, 2874 w. MS, *m/z* (EI, relative intensity, %): 260 (M^+, 32), 259 (13), 245 (27), 232 (28), 231 (100), 204 (18), 176 (48), 175 (13), 173 (16) HRMS Calcd for $C_{15}H_{24}N_2Si$ ($[M+H]^+$): 260.1709; found: 260.1709.

2-[(Triethylsilyl)methyl]benzo[*d*]thiazole (2o).



2o was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.19 in hexane/EtOAc = 40/1) in 85% yield (67.2 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.65 (q, *J* = 7.9 Hz, 6H), 0.96 (t, *J* = 7.9 Hz, 9H), 2.68 (s, 2H), 7.26 (td, *J* = 7.7, 1.9 Hz, 1H), 7.38 (td, *J* = 7.7, 1.9 Hz, 1H), 7.75 (d, *J* = 8.0 Hz, 1H), 7.87 (d, *J* = 8.0 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: 3.4, 7.3, 21.8, 121.2, 121.8, 124.0, 125.7, 135.3, 153.7, 170.3. IR (ATR): 2952 w, 2874 w. MS, *m/z* (EI, relative intensity, %): 263 (M^+, 7) 262 (12), 248 (23), 236 (10), 235 (20), 234 (100), 206 (22), 87 (44), 86 (17), 59 (25). HRMS Calcd for $C_{14}H_{22}NSSi$ ($[M+H]^+$): 264.1242; found: 264.1243.

2-[(Triethylsilyl)methyl]thiazole (2p).



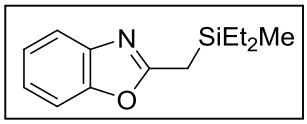
2p was obtained by flash column chromatography on NH_2-modified silica-gel (R_f = 0.26 in hexane/EtOAc = 50/1) in 73% yield (47.0 mg) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 0.60 (q, *J* = 8.0 Hz, 6H), 0.94 (t, *J* = 8.0 Hz, 9H), 2.59 (s, 2H), 7.04 (d, *J* = 3.4, Hz, 1H), 7.57 (d, *J* = 3.4, Hz, 1H).^{13}C NMR ($CDCl_3$) δ: 3.2, 7.3, 20.2, 116.8, 142.1, 169.4. IR (ATR): 2952 w, 2875 w. MS, *m/z* (EI, relative intensity, %): 213 (M^+, 0.2), 198 (40), 185 (17), 184 (100), 170 (12), 157 (14), 156 (36), 129 (20), 128 (22), 115 (11),

87 (70), 86 (21), 59 (45), 58 (17). HRMS Calcd for $C_{10}H_{19}NSSi$ (M^+): 213.1007; found: 213.1009.

2-[(Diethylmethylsilyl)methyl]benzo[*d*]oxazole (3a) and **2-[Bis(diethylmethylsilyl)methyl]-benzo[*d*]oxazole (3a').**

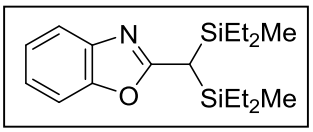
After reacting **1a** (68.3 mg, 0.3 mmol) with $HSiEt_2Me$ (122.7 mg, 1.2 mmol) under the standard reaction conditions, the reaction mixture was passed through an NH_2-modified silica-gel column to isolate **3a** in 17% yield (12.1 mg, R_f = 0.17 in hexane/ EtOAc = 40/1) and **3a'** in 69% yield (68.9 mg, R_f = 0.49 in hexane/ EtOAc = 40/1), as colorless oils, respectively.

*2-[(Diethylmethylsilyl)methyl]benzo[d]oxazole (**3a**).*



^{1}H NMR ($CDCl_3$) δ: 0.08 (s, 3H), 0.63 (q, *J* = 7.9 Hz, 4H), 0.96 (t, *J* = 7.9 Hz, 9H), 2.42 (s, 2H), 7.20-7.22 (c, 1H), 7.41-7.43 (c, 1H), 7.59-7.61 (c, 1H).^{13}C NMR ($CDCl_3$) δ: -5.8, 5.2, 7.1, 16.7, 109.9, 118.9, 123.7, 123.9, 142.2, 150.9, 167.8. IR (ATR): 2954 w, 2876 w. MS, *m/z* (EI, relative intensity, %): 233 (M^+, 13), 232 (28), 218 (10), 205 (19), 204 (100), 190 (10), 177 (26), 176 (45), 150 (12), 101 (15), 73 (77), 72 (25), 45 (26). HRMS Calcd for $C_{13}H_{20}NOSi$ ([M+H]$^+$): 234.1314; found: 234.1310. **3a** was produced as a sole product by the reaction under the revised reaction conditions shown in Scheme 3, and isolated in 69% yield.

*2-[Bis(diethylmethylsilyl)methyl]benzo[d]oxazole (**3a'**).*



^{1}H NMR ($CDCl_3$) δ: 0.13 (s, 6H), 0.49-0.68 (c, 8H), 0.88 (t, *J* = 7.9 Hz, 6H), 0.93 (t, *J* = 7.9 Hz, 6H), 2.22 (s, 1H), 7.17-7.26 (c, 2H), 7.40 (d, *J* = 7.5 Hz, 1H), 7.57 (d, *J* = 7.5 Hz, 1H).^{13}C NMR ($CDCl_3$) δ: -4.5, 6.1, 6.3, 7.4, 7.5, 18.2, 109.7, 118.7, 123.1, 123.7, 142.5, 150.8, 169.6. IR (ATR): 2953 w, 2876 w. MS, *m/z* (EI, relative intensity, %): 333 (M^+, 10), 332 (13), 306 (10), 305 (30), 304 (100), 277 (16), 276 (62), 248 (11), 246 (12), 218 (12), 101 (53), 87 (14), 73 (84), 59 (18). HRMS Calcd for $C_{18}H_{31}NSi_2$ (M^+): 333.1944; found: 333.1940.

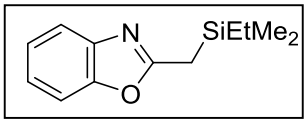
2-[(Ethyldimethylsilyl)methyl]benzo[*d*]oxazole (4a) and 2-[Bis(ethyldimethylsilyl)methyl]-benzo[*d*]oxazole (4a').

After reacting **1a** (68.3 mg, 0.3 mmol) with $HSiEtMe_2$ (105.9 mg, 1.2 mmol) under the standard reaction conditions, the reaction mixture was passed through an NH_2-modified silica-gel column to isolate **4a'** in 66% yield (61.0 mg, R_f = 0.49 in hexane/ EtOAc = 40/1) as a colorless oil. However, no **4a** was obtained, probably due to decomposition during chromatographic

separation.

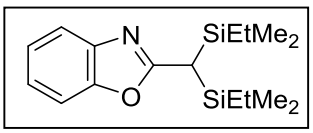
1a was also reacted with $HSiEtMe_2$ under the reaction conditions shown in Scheme 3, instead of $HSiEt_2Me$, to afford a mixture of **4a** and **4a'** in 41% and 51% yields, respectively, which were determined from ^1H NMR spectra with 1,3-dihydro-2-benzofuran as an internal standard. After the reaction, the reaction mixture was passed through an NH_2-modified silica-gel column to isolate **4a** in 3% yield (8.0 mg, R_f = 0.17 in hexane/ EtOAc = 40/1) and **4a'** in 47% yield (43.1 mg, R_f = 0.49 in hexane/ EtOAc = 40/1), as colorless oils, respectively.

*2-[(Ethyldimethylsilyl)methyl]benzo[d]oxazole (**4a**).*



^1H NMR ($CDCl_3$) δ: 0.11 (s, 6H), 0.63 (q, *J* = 8.0 Hz, 2H), 0.98 (t, *J* = 8.0 Hz, 3H), 2.43 (s, 2H), 7.21-7.29 (c, 2H), 7.42-7.46 (c, 1H), 7.60 (dd, *J* = 7.1, 2.1 Hz, 1H). ^{13}C NMR ($CDCl_3$) δ: -3.5, 7.0, 7.2, 18.4, 119.3, 110.0, 119.0, 123.7, 123.9, 142.1, 150.9, 167.3. IR (ATR): 2955 w, 2876 w. MS, *m/z* (EI, relative intensity, %): 219 (M^+, 25), 218 (68), 204 (42), 191 (28), 190 (38), 176 (38), 150 (23), 135 (21), 87 (25), 86 (10), 59 (100), 58 (22). HRMS Calcd for $C_{12}H_{18}NOSi$ ($[M+H]^+$): 220.1158; found: 220.1156.

*2-[Bis(ethyldimethylsilyl)methyl]benzo[d]oxazole (**4a'**).*



^1H NMR ($CDCl_3$) δ: 0.11 (s, 6H), 0.14 (s, 6H), 0.56 (c, 4H), 0.91 (t, *J* = 8.1 Hz, 6H), 2.18 (s, 2H), 7.17-7.26 (c, 2H), 7.38-7.41 (c, 1H), 7.57-7.59 (c, 1H).^{13}C NMR ($CDCl_3$) δ: -2.4, -2.2, 7.3, 8.1, 20.8, 109.7, 118.7, 123.1, 123.7, 142.5, 150.8, 169.6. IR (ATR): 2954 w, 2876 w. MS, *m/z* (EI, relative intensity, %): 305(M^+, 20), 304 (30), 290 (33), 277 (21), 276 (64), 262 (14), 249 (12), 248 (43), 232 (17), 222 (17), 208 (14), 204 (13), 178 (10), 87 (68), 73 (33), 59 (100). HRMS Calcd for $C_{16}H_{27}NOSi_2$ (M^+): 305.1631; found: 305.1629.

5.5 References and Notes

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Conclusion

Some new types of the C(sp^3)-H bond silylations catalyzed by $Ir_4(CO)_{12}$ or (POCOP^{t}Bu)IrHCl/$NaBAr^F_4$ was developed and reported herein. The key to success for these reactions is the generation of an electrophilic silicon species as a key intermediate in the catalytic cycle.

Chapter 1 contains a discussion of the iridium-catalyzed regioselective C(sp^3)-H silylation of 4-alkypyridines at the α-position with hydrosilanes. The low product yields of 2-substituted 4-methylpyridines were improved markedly by the addition of a catalytic amounts of 3,5-dimethylpyridine. This is the rare example of non-chelation-assisted C(sp^3)-H bond silylations with hydrosilanes in transition metal catalysis. An unprecedented C4 selectivity was observed when a polyalkyl-substituted pyridine such as 2,4-dimethylpyridine was used as a substrate.

Chapter 2 deals with the iridium-catalyzed silylation of C(sp^3)-H bonds in 2-alkylpyridine derivatives with hydrosilanes. The addition of 3,5-dimethylpyridine was also essential for the success of the reaction.

Chapter 3 is concerned with the iridium-catalyzed C(sp^3)-H silylation of 2-alkyl-1,3-azoles at the α-position in the alkyl group. Screening of complexes as catalysts that have the ability to electrophilically activate the hydrosilane, revealed that a cationic pincer iridium complex (POCOP^{t}Bu)IrHCl showed a high degree of catalytic activity.

A number of catalytic silylations of C(sp^2)-H bonds, involving the generation of electrophilic silicon species followed by an electrophilic attack on the silicon atom, such as Friedel-Crafts type C-H silylation, have been reported to date. On the other hand, to the best my knowledge, this is the first example of the electrophilic silylation of C(sp^3)-H bonds. These findings provide a promising starting point for the further development of a variety of the electrophilic silylation of C(sp3)-H bonds.

One advantage of the present reactions, compared to the conventional method in which organometallic reagents such as Grignard reagents are used, is its broader functional group compatibility. A variety of functional groups, even bromide and chloride, did not affect the reaction. This result shows that the reactions reported in this thesis provide a simple and useful method for the synthesis of various types of benzylated silyl compounds.

List of Publications

(1) Iridium-Catalyzed Regioselective C(sp^3)–H Silylation of 4-Alkylpyridines at the Benzylic Position with Hydrosilanes Leading to 4-(1-Silylalkyl)pyridines
Yoshiya Fukumoto, Masaya Hirano, Naoto Chatani.
ACS Catal. **2017**, *7*, 3152.

(2) $Ir_4(CO)_{12}$-Catalyzed Benzylic C(sp^3)-H Silylation of 2-Alkylpyridines with Hydrosilanes Leading to 2-(1-Silylalkyl)pyridines
Yoshiya Fukumoto, Masaya Hirano, Nao Matsubara, Naoto Chatani.
J. Org. Chem. **2017**, *82*, 13649.

(3) An Cationic Iridium-Catalyzed C(sp^3)-H Bond Silylation of 2-Alkyl-1,3-azoles at the α-Position in the 2-Alkyl Group Leading to 2-(1-Silylalkyl)-1,3-azoles
Masaya Hirano, Yoshiya Fukumoto, Nao Matsubara, Naoto Chatani.
Chem. Lett. in press.

Supplementary List of Publication

(1) Rhodium-Catalyzed Anti-Markovnikov Hydrohydrazination of Terminal Alkynes with *N*-Alkyl- and *N*,*N*-Dialkylhydrazines
Yoshiya Fukumoto, Akihiro Ohmae, Masaya Hirano, Naoto Chatani.
Asian J. Org. Chem. **2013**, *2*, 1036.