# Rhodium-catalyzed and Coordination-assisted Regioselective Alkenylation of Aromatic C–H Bonds with Terminal Silylacetylenes

Takashi Katagiri, Tomoya Mukai, Tetsuya Satoh, Koji Hirano, and Masahiro Miura*
*Department of Applied Chemistry, Faculty of Engineering, Osaka University, Suita, Osaka 565-0871*

(Received November 14, 2008; CL-081075; E-mail: miura@chem.eng.osaka-u.ac.jp)

A number of aryl-*N*-heterocycles and aromatic imines efficiently undergo ortho alkenylation via C–H bond cleavage upon treatment with bulky terminal silylacetylenes, typically triisopropylsilylacetylene, in the presence of $[RhCl(cod)]_2/PAr_3$ as catalyst.

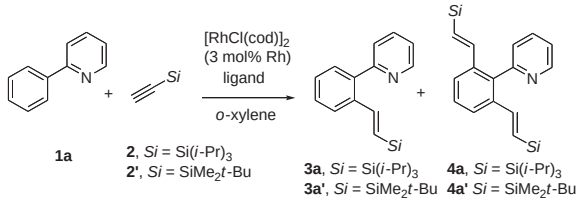
Transition-metal-catalyzed C–C bond formation through C–H bond cleavage has attracted much attention from the atom-economic point of view, and various catalytic processes involving different modes to activate the ubiquitously available bond have been developed.[1] Among the most promising activation strategies is to utilize the proximate effect by coordination of a functional group in a given substrate to the metal center of a catalyst, which brings about regioselective C–H bond activation and functionalization. As one of such catalytic reactions, the direct ortho alkylation of aromatic compounds bearing a suitable oxygen or nitrogen-containing functional group is now known to selectively take place by treatment with alkenes. The work of Murai and co-workers using aromatic ketones as substrates under ruthenium catalysis is a significant pioneering milestone for the C–H alkylation.[2] A number of relevant reactions with internal alkynes in place of alkenes that allow ortho alkenylation have also been realized.[3] However, successful examples with terminal alkynes have been very limited,[4] which is attributed to the fact that acetylenic C–H bonds are, in most cases, more reactive than aromatic C–H bonds. As a rare example, Jun and co-workers reported that some aromatic imines react with aliphatic terminal alkynes in the presence of a rhodium catalyst.[4a] We reported the related rhodium-catalyzed hydroacylation of alkynes including a number of terminal ones with salicylaldehyde.[4c] Very recently, Zhang and co-workers described the ruthenium-catalyzed reaction of 2-phenylpyridines with aromatic and aliphatic terminal alkynes.[4d,5]

In the course of our study of catalytic coupling reactions with alkynes,[6a–6c,7] we have unexpectedly observed that a number of aryl-*N*-heterocycles and aromatic imines efficiently undergo rhodium-catalyzed ortho alkenylation on treatment with bulky terminal silylacetylenes. This appears to be of considerable interest, since terminal silylacetylenes have been recently demonstrated to be effective substrates in a number of catalytic cross-dimerization reactions with different terminal or internal alkynes to produce the corresponding enyne compounds,[6] in which the silylacetylenes act as acetylene donors, as they are relatively reactive toward C–H bond cleavage. Nevertheless, the acetylenes are capable of acting as aromatic C–H acceptors in the present reaction.

When 2-phenylpyridine (**1a**) (0.5 mmol) was treated with triisopropylsilylacetylene (**2**) (1 mmol, 2 equiv) in the presence of $[RhCl(cod)]_2$ (0.0075 mmol, 3 mol % Rh) and $PPh_3$ (0.03 mmol, 6 mol %) as catalyst and ligand in refluxing *o*-xylene for 3 h, the corresponding 2,6-dialkenylated product **4a** (74%) was produced together with monoalkenylated **3a** (26%) (Table 1, Entry 1). Using 3 equiv of **2** and $PCyPh_2$ (Cy = cyclohexyl) in place of $PPh_3$ afforded **4a** in 95% yield after 9 h (Entry 3). In each of Entries 1–3, formation of dimerized **2** as the minor byproduct was detected by GC-MS, while it was readily separable. It was found that P(2-furyl)$_3$ was a less effective ligand (Entry 4), but no dimer of **2** was detected. Thus, **3a** (77%) was selectively obtained with 1 equiv of **2** using P(2-furyl)$_3$ (Entry 5). The reaction did not proceed without any phosphine ligand (Entry 6). The reaction of **1a** with *tert*-butyldimethylsilylacetylene (**2′**) (2 equiv) in place of **2** proceeded somewhat slowly to give a mixture of **3a′** and **4a′** (Entry 7). As expected, **3a′** was obtained as the predominant product in the reaction with 1 equiv of **2′** using P(2-furyl)$_3$ (Entry 8). The ligand $PCyPh_2$ was unexpectedly not effective in the reaction with **2′** (Entry 9). The reaction of **1a** with trimethylsilylacetylene (3 equiv) using $PPh_3$ in a sealed tube was sluggish and monoalkenylated product was detected in only ca. 25% GC yield. Use of phenylacetylene and 1-octyne was not successful as reported previously.[3d]

We next examined the alkenylation of a number of aryl-*N*-heterocycles and aromatic imines **1** with silylacetylene **2** (Table 2). The reaction of 2,2′-bipyridyl (**1b**) in the presence of $[RhCl(cod)]_2$ and $PPh_3$ smoothly proceeded to give the corresponding 3,3′-dialkenylated product **4b** in quantitative yield (Entry 1). In this reaction, use of P(2-furyl)$_3$ gave a mixture of

**Table 1.** Reaction of 2-phenylpyridine (**1a**) with terminal silylacetylene **2** or **2′** [a]

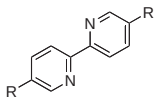
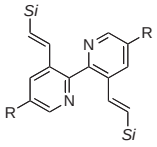
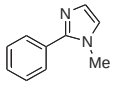
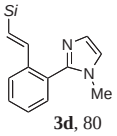
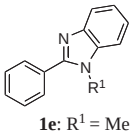
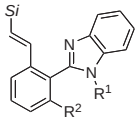
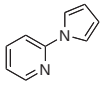
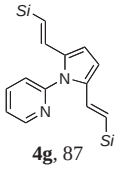
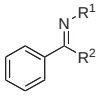
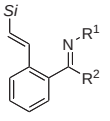



**1a**
**2**, *Si* = Si(*i*-Pr)$_3$
**2'**, *Si* = SiMe$_2$*t*-Bu
**3a**, *Si* = Si(*i*-Pr)$_3$ **4a**, *Si* = Si(*i*-Pr)$_3$
**3a'**, *Si* = SiMe$_2$*t*-Bu **4a'** *Si* = SiMe$_2$*t*-Bu

| Entry | Alkyne /equiv[b] | Ligand | Time/h | Yield[c]/% | |
|---|---|---|---|---|---|
| | | | | **3a** (or **3a′**) | **4a** (or **4a′**) |
| 1 | **2** (2) | $PPh_3$ | 3 | 26 | 74 |
| 2 | **2** (3) | $PPh_3$ | 6 | 15 | 85 |
| 3 | **2** (3) | $PCyPh_2$ | 9 | 2[d] | 95 |
| 4 | **2** (3) | P(2-furyl)$_3$ | 9 | 22[d] | 75[d] |
| 5 | **2** (1) | P(2-furyl)$_3$ | 3 | 77 | 4 |
| 6 | **2** (1) | none | 3 | 0 | 0 |
| 7 | **2′** (2) | $PPh_3$ | 3 | 67 | 33 |
| 8 | **2′** (1) | P(2-furyl)$_3$ | 3 | 77 | 7 |
| 9 | **2′** (2) | $PCyPh_2$ | 3 | 9[d] | 5[d] |

[a]Reaction conditions: [**1a**]:[Rh]:[ligand] = 0.5:0.015:0.03 (in mmol), in *o*-xylene (5 mL) at 160 °C (bath temp.) under $N_2$. [b]Relative to **1a**. [c]Isolated yield based on the amount of **1a** used. [d]Determined by GC.

**Table 2.** Reaction of aryl-*N*-heterocycles and imines **1** with triisopropylsilylacetylene **2**[a]

| Entry | Substrate | **2** /equiv[b] | Time /h | Product,[c] Yield[d]/% |
|---|---|---|---|---|
| 1 |  **1b**: R = H | 3 | 1 |  **4b**: R = H, 99 |
| 2 | **1c**: R = Me | 3 | 1 | **4c**: R = Me, 88 |
| 3[e,f] |  **1d** | 2 | 3 |  **3d**, 80 |
| 4[e,f] |  **1e**: $R^1$ = Me | 2 | 6 |  **3e**: $R^1$ = Me, $R^2$ = H, 84 |
| 5[g] | **1f**: $R^1$ = H | 3 | 48 | **4f**: $R^1$ = H, $R^2$ = (*E*)-*Si*$C_2H_4$, 74 |
| 6[e] |  **1g** | 3 | 3 |  **4g**, 87 |
| 7[h] |  **1h**, $R^1$ = Bn, $R^2$ = Me[i] | 2 | 3 |  **3h**, $R^1$ = Bn, $R^2$ = Me, 80[i,j] |
| 8[h] | **1i**, $R^1$ = H, $R^2$ = Ph | 2 | 8 | **3i**, $R^1$ = H, $R^2$ = Ph, 48 |
| 9[h] | **1j**, $R^1$ = OH, $R^2$ = Me | 2 | 1 | **3j**, $R^1$ = OH, $R^2$ = Me, 66 |

[a]Reaction conditions: [**1**]:[Rh]:[$PPh_3$] = 0.5:0.015:0.03 (in mmol), in *o*-xylene (4–5 mL) at 160 °C (bath temp.) under $N_2$. [b]Relative to **1**. [c]*Si* = Si(*i*-Pr)$_3$. [d]Isolated yield based on the amount of **1** used. [e]Reaction in a half scale. [f]Reaction in mesitylene at 160 °C (bath temp.). [g]Reaction with (4-$ClC_6H_4$)$_3$P in place of $PPh_3$. [h]Reaction in toluene at 135 °C (bath temp.). [i]Syn/anti = 2:8. [j]Determined by GC.

monoalkenylated product and **4b** (ca. 3:1) even with 1 equiv of **2**. The dialkenylation of 5,5′-dimethyl-2,2′-bipyridyl (**1c**) also took place to afford compound **4c** (Entry 2). 1-Methyl-2-phenyl-1*H*-imidazole (**1d**) and 1-methyl-2-phenyl-1*H*-benzimidazole (**1e**) selectively underwent monoalkenylation even in mesitylene to give compounds **3d** and **3e** in 80% and 84% yields, respectively (Entries 3 and 4). This is probably due to steric hindrance of the 1-methyl group. Thus, 2-phenyl-1*H*-benzimidazole (**1f**) afforded the expected dialkenylated product **4f**. In this case, **4f** (74%) was selectively obtained along with monoalkenyalted product (ca. 5%) by elongation of reaction time and using P(4-$ClC_6H_4$)$_3$ as ligand (Entry 5). 1-(2-Pyridinyl)pyrrole (**1g**) smoothly underwent dialkenylation to give **4g** in 87% yield (Entry 6). In the reactions of benzylimine of acetophenone (**1h**), benzophenone imine (**1i**), and acetophenone oxime (**1j**) in toluene, the corresponding monoalkenylated products **3h**–**3j** were produced with substantial yields (Entries 7–9).

The success of the present aromatic C–H alkenylation is considered to be due to the fact that the ortho C–H activation of **1** smoothly occurs even in the presence of **2**. The favorable N-coordination of **1** to the metal with C–H agostic interaction even in the presence of **2** would be due to the bulkiness of **2**. However, the reaction of **1a** with a bulky terminal acetylene, 1-trimethylsilyloxy-1,1-diphenyl-2-propyne [HCC-$CPh_2$-($OSiMe_3$)][6b] was not successful even with P(2-furyl)$_3$ as ligand, mainly giving its dimerized compound. Thus, elucidation of the predominant factors affecting relative ease of cleavage of aromatic and acetylenic C–H bonds is a subject of further investigation.

In summary, we have found that a number of aryl-*N*-heterocycles as well as imines unexpectedly and efficiently undergo rhodium-catalyzed ortho alkenylation upon treatment with terminal silylacetylenes.[8] This may provide an effective straightforward method for preparing a series of mono- or divinylated aromatic compounds.

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