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1,2,3-Triazol-5-ylidene–palladium complex catalyzed Mizoroki–Heck and Sonogashira coupling reactions

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ABSTRACT

The bis-1,4-dimesityl-1,2,3-triazol-5-ylidene–palladium complex (**1a**) successfully catalyzes the Mizoroki–Heck and Sonogashira coupling reactions with aryl bromides to give the corresponding alkenes and alkynes, respectively, in good to excellent yields. In the Mizoroki–Heck reaction, electron-rich, electron-poor, and functionalized aryl bromides and alkenes are tolerated, while the substrates are limited to electron-poor aryl halides in the Sonogashira coupling reaction. The palladium complex also catalyzes cross-coupling reactions with aryl chlorides to give higher yields of products than does the bis-IMes–Pd complex analogue (**2**), under specific conditions.

1. Introduction

Since its discovery 20 years ago, *N*-heterocyclic carbenes (NHCs) have gained rapid popularity as versatile ligands for metal complexes.[1] In particular, numerous Pd–NHC complexes have been prepared and their catalytic activity in cross-coupling reactions, such as Suzuki–Miyaura and Mizoroki–Heck cross-coupling reactions[2] have been investigated. The majority of NHC ligands is based on an imidazole framework and imidazol-2-ylidenes (**A**) and 1,2,4-triazol-5-ylidenes (**B**) (Fig. 1),[3] which are classified as normal NHCs are frequently used. Crabtree first reported an abnormally bonded NHC (*a*NHC, **C**) complex in which the imidazolium moiety was coordinated at the C4 position.[4] Nolan[5] and Hong[6] demonstrated that Pd–*a*NHC complex was more effective than the corresponding normal NHC complex in the Suzuki–Miyaura and Mizoroki–Heck reactions; and this enhanced catalytic activity may be due to the stronger σ-donor ability of *a*NHC compared with that of normal NHCs.

Albrecht first reported an *a*NHC ligand based on 1,2,3-triazol-5-ylidene (**D**) and its metal complexes.[7] Bertrand demonstrated that the donor property of 1,2,3-triazol-5-ylidene was superior to those of imidazol-2-ylidenes and 1,2,4-triazol-5-ylidenes in the vibrational spectra study of its iridium carbonyl complexes.[8] Abnormal NHC ligands and their complexes show potential use for unique catalytic activity in organic reactions.[9] Sankararaman prepared a pyrrolidinyl 1,2,3-triazol-5-ylidene–palladium complex and examined its catalytic effectiveness in the Suzuki–Miyaura coupling reaction,[10] with aryl bromides as the substrate. Based on these previous studies, we envision that the 1,4-dimesityl substituted 1,2,3-triazol-5-ylidene (TMes) ligand precursor should be an effective ligand as is its analogue, IMes [1,3-bis(mesityl)imidazol-2-ylidene], which is an effective imidazole-carbene ligand owing to its electronically rich and sterically hindered mesityl groups (Fig. 2).

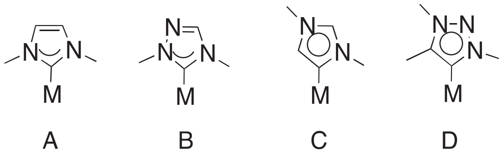
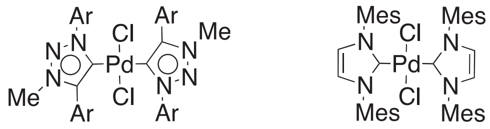


Fig. 1. Traditional NHCs (**A** and **B**) and *a*NHCs (**C** and **D**) bound to transition metals.



1a: Ar = Mes
1b: Ar = Ph

2

Fig. 2. *trans*-Bis(1,2,3-triazol-5-ylidene)palladium (**1**) and *trans*-bis(imidazol-2-ylidene)palladium (**2**).

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In our preliminary study, we reported the synthesis of *trans*-$(TMes)_2PdCl_2$ (**1**a) and its catalytic behaviour in the Suzuki–Miyaura coupling reaction with aryl chlorides.[11] The reaction successfully yielded the coupling product in high amounts, and the complex proved to be particularly effective for the reaction between the sterically hindered aryl chlorides and aryl boronic acids. The palladium complex **1a** was revealed to have a higher catalytic activity than that of the corresponding imidazole NHC–Pd complex $[(IMes)_2PdCl_2]$ (**2**), under the same conditions.

We recently demonstrated that the 1,2,3-triazole NHC–copper complex was superior to the imidazole NHC–copper analogue in the CuAAC reaction.[12] The triazole NHC–copper complex significantly accelerated the reaction, and in the reaction between a sterically hindered alkyne and a sterically hindered azide, it successfully yielded a highly sterically crowded triazole. To establish the advantages of the 1,2,3-triazole NHC ligand and its palladium complexes in synthetic reactions, we extend the use of the palladium catalyst to other cross-coupling reactions. Previously we reported the Mizoroki–Heck coupling reaction between bromobenzene with *tert*-butyl acrylate using **1a** as a catalyst.[11] Herein, we describe Mizoroki–Heck and Sonogashira coupling reactions using **1** as a catalyst.

2. Results and discussion

To evaluate the activity of complex **1a**,**b**, we carried out a kinetic study of the Mizoroki–Heck coupling reaction of bromobenzene with *tert*-butyl acrylate. The yield versus time graphs are shown in Fig. 3 for **1a**,**b**. The reaction was carried out in dimethylacetamide (DMA) at 150 °C with loading 1.0 mol % of the palladium complex and was followed by gas chromatography (GC). The yield was determined by GC by using biphenyl as an internal standard. As seen in the graph, there was an initial 1-h induction period in the reaction with **1a**, and after this the reaction was accelerated and 80% product yield was achieved after 3 h. As expected, the Pd complex **1b** was less active catalyst giving 40% product yield after 8 h. The lower activity of **1b** was due to the poor electron-donor and low sterically crowded TPh ligand. During the initial 30 min the active TMes–Pd(0) complex was generated.[13] An induction period was also observed in the reaction with **1b**, and it took more than 3 h to generate the active catalyst, which was not as active as **1a**.

The reaction could be carried out with low catalyst loading or at lower temperature, however, the yield decreased although the reaction time was extended; 0.5 mol %, 85% (150 °C, 15 h), 0.1 mol %, 62% (150 °C, 15 h), 1 mol %, 56% (130 °C, 15 h) and 1.0 mol %, 7% (110 °C, 15 h). The coupling reactions between a variety of aryl bromides and *tert*-butyl acrylate were examined to explore the scope of the **1a** catalyzed Mizoroki–Heck coupling reaction. The results are summarized in Table 1. The trans-isomers were obtained as the sole products in excellent yields irrespective of the stereoelectronic properties of the benzene substituents. Electronically activated and deactivated aryl bromides tolerated the reaction, and the corresponding cinnamate esters were obtained in excellent yields (entries 1, 2 and 4–6). However, *o*-bromoanisole and *o*-nitrobromobenzene produced low product yields of 51% and 0%, respectively (entries 3 and 7). The coupling with other aromatic rings, such as 1-bromonaphthalene (entry 10) gave the corresponding α, β-unsaturated esters in quantitative yields. The heteroaromatic bromides, such as 3-bromopyridine and 2-bromothiophene (entries 12–13) coupled with *tert*-butyl acrylate to produce the corresponding products in low to moderate yields. On the other hand, the reaction with 2-bromopyridine hardly gave the coupling product (entry 11). Poor to low yields of the products may be due to heteroatoms coordinating with the palladium, therefore interfering with the catalysis role of the palladium complex.

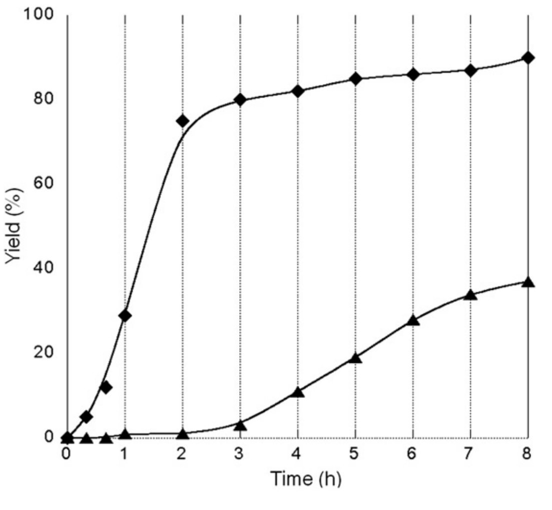
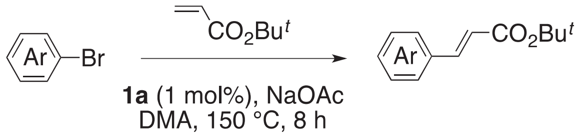


Fig. 3. Time versus yield (%) graph for the palladium catalyzed Mizoroki–Heck reaction of bromobenzene with *tert*-butyl acrylate: ◆ **1a**; ▲ **1b**.

Table 1

The scope of aryl bromides in the Mizoroki–Heck reaction with *tert*-butyl acrylate[a]



Entry	Ar	Yield[b] (%)
1	*o*-MeC_6H_4	92
2	*p*-MeC_6H_4	98
3	*o*-$MeOC_6H_4$	51
4	*p*-$MeOC_6H_4$	88
5	*p*-FC_6H_4	98
6	*p*-$CH_3COC_6H_4$	97
7	*o*-$NO_2C_6H_4$	0
8	*p*-$NO_2C_6H_4$	93
9	*m*-$NO_2C_6H_4$	94
10	1-$C_{10}H_8$	97
11	2-Pyridyl	0
12	3-Pyridyl	32
13	2-Thiophenyl	69

[a] Compound **1a** (0.005 mmol), aryl bromide (0.5 mmol), *tert*-butyl acrylate (0.75 mmol), NaOAc (1.0 mmol), DMA (1.5 mL); 150 °C, 8 h.

[b] Isolated yield: *trans/cis*≅99.9/0.1.

We then examined the reactions *p*-bromotoluene with various substituted styrenes under the same conditions as described above. The results are summarized in Table 2. The *trans*-stilbene derivatives were obtained from either electron-rich or electron-poor styrenes in good yields. However, the reaction with *o*-methylstyrene gave the corresponding coupling product in low yield probably due to steric hindrance. The reaction with 2-vinylpyridine gave the corresponding coupling product in low yield (entry 8); however, the reaction of 2-bromopyridine with *tert*-butyl acrylate did not give the coupling product at all (Table 1, entry 11).

As the above reactions with aryl and heteroaryl bromides and alkenes were tolerated, we were encouraged to attempt the reaction with aryl chlorides. Aryl chlorides have rarely been used for Mizoroki–Heck reaction, and addition of ammonium halide is often necessary to obtain a satisfactory yield product.[2c,14] It is interesting that moderate yields (64–69%) of products could be obtained in the reaction with *p*-chloronitrobenzene and *p*-chlorobenzonitrile in the absence of ammonium halide by using **1a** as a catalyst (entries 2 and 4, Table 3). On the other hand, bis-imidazole carbene $[(IMes)_2PdCl_2]$ (**2**) gave low yields of the products (45% and 27%,