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Report

copper(I) complex, *N*-arylation reactions, N-heterocyclic carbene, (hetero)aryl chlorides, nitrogen heterocycles

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N-Heterocyclic Carbene Copper(I) Complex Catalyzed Coupling of (Hetero)aryl Chlorides and Nitrogen Heterocycles: Highly Efficient Catalytic System

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A highly efficient catalytic system for the *N*-arylation reactions of (hetero)aryl chlorides and nitrogen heterocycles with a copper(I) complex containing a 1,10-phenanthroline analogue N-heterocyclic carbene (NHC) has been reported. The complex was characterized by ^{1}H and ^{13}C NMR spectroscopy and elemental analysis, and its structure was determined by single-crystal X-ray diffraction. The NHC-copper(I) complex was employed as pre-catalyst for Ullmann type *N*-arylation reactions of (hetero)aryl chlorides with various azoles. A variety of hindered and functionalized azoles and (hetero)aryl chlorides were transformed in good to excellent yields.

Background and Originality Content

N-aryl heterocycles, as important organic compounds in natural products, are widely used in medicine, biology, materials and other fields. [1] Transition-metal-catalyzed Ullmann-type C-N bond coupling has become a powerful and efficient tool to synthesize them which has been widely used in organic synthesis. [2] Copper is one of the most often used metals for this transformation. [3] Unfortunately, the application of copper-mediated *N*-arylation reactions in the synthesis of N-arylated heterocyclic compounds has some challenges. These reactions usually require elevated reaction temperatures, high catalyst loadings, or selective halide substrates (aryl iodides or aryl bromides). All of these limit their application in industry from a practical point of view. In order to solve these problems and improve catalytic efficiency, much effort has been made in the design of ligands to promote copper-catalyzed Ullmann-type reactions. During the past years, a series of effective ligands, including diamines, [4] phenanthroline, [5] amino acids, [6] β-diketones, [7] 8-hydroxyquinolines, [8] Schiff base, [9] ethylene glycoll, [10] 2,2'-bipyridine, [5e, 11] carbohydrates, [12] and others, [13] have been reported.

Although the above progress has been achieved, most of the reaction halide substrates are still aryl iodides or aryl bromides and aryl chlorides are rarely used as cross-coupling electrophiles. Even if they are used, harsh reaction conditions and high catalyst loadings are usually needed. To overcome above drawbacks, we need to develop more highly active catalytic systems.

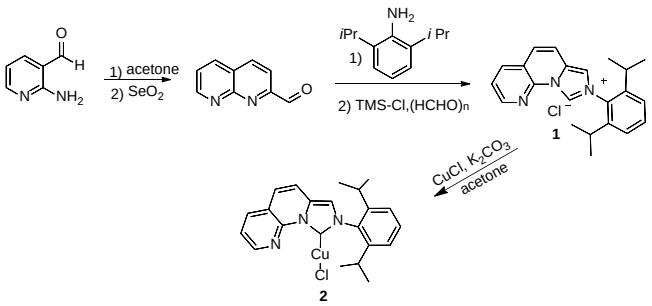
N-Heterocyclic carbenes (NHCs) are a class of effective and versatile ligands owing to their strong σ-donor properties and chemical robustness. [14] At present, a large number of NHC-Cu complexes with different structures and properties have been synthesized and since the first N-heterocyclic carbene copper complex was separated in 1993. [15] The use of NHCs as ligands in Cu/ligand catalytic systems has led to a variety of satisfactory developments. [16] However, no more attention has been paid to the Ullmann-type *N*-arylation reactions of (hetero)aryl chlorides and nitrogen heterocycles catalyzed by NHC-Cu complexes.

Herein, a new copper(I) complex containing a 1,10-phenanthroline analogue NHC is reported. As a pre-catalyst, it is applied to the *N*-arylation reactions of (hetero)aryl chlorides with nitrogen heterocycles and works well with a wide range of azoles at a low catalyst loading (1 mol %).

Results and Discussion

The synthetic route for copper(I) complex **2** is illustrated in Scheme 1. 1,8-Naphthyrido[1,2-a]-(2',6'-diisopropylphenyl) limidazolium chloride **1** was synthesized according to previous reports. [17] By adding commercially available CuCl and K_2CO_3 with **1** in the presence of acetone, the copper(I) complex **2** was prepared. The complex was characterized by NMR spectroscopy (see Supporting Information).

Scheme 1. Synthesis of copper(I) complex **2.**



Crystal of copper(I) complex **2** was grown by slow evaporation from a mixed CH_2Cl_2/petroleum ether solvent. The molecular structure of complex **2** was determined by X-ray single-crystal diffraction, as shown in Figure **1**. Complex **2** crystallizes in the orthorhombic space group $P2_12_12_1$, which is a mononuclear structure containing one ligand, one Cu^I ion and one Cl^- anion. The Cu^I center is linked to one carbon atom (C1) of carbene ligand and one Cl^- ion (Cl1) to form nearly linear coordinated geometry (177.40(9) º for the angle of C1-Cu1-Cl1). The bond angles for N1-C1-N2, N1-C1-Cu1 and N2-C1-Cu1 are 102.6(2) º, 131.7(2) º and 125.8(2) º, indicating that the Cl-Cu-C unit is almost coplanar with the fused ring. No obvious Cu···N contact is found. The bond lengths of Cu1-C1 and Cu1-Cl1 in complex **2** are 1.869(3) and 2.1099(8) Å, respectively, which lie in the expected range of Cu^I-C and Cu^I-N bonds.

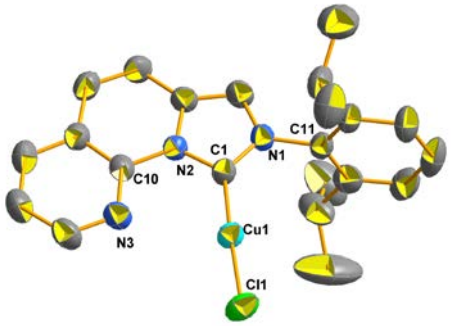
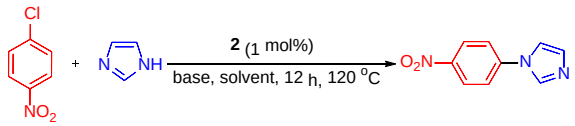


Figure 1 Perspective view of copper(I) complex **2**. Ellipsoids are drawn at the 50% probability level. Selected interatomic distances (Å) and bond angles (deg): C1-N1 = 1.355(3), C1-N2 = 1.369(3), C1-Cu1 = 1.869(3), Cu1-Cl1 = 2.1099(8); N1-C1-N2 = 102.6(2), N1-C1-Cu1 = 131.7(2), N2-C1-Cu1 = 125.8(2), C1-Cu1-Cl1 = 177.40(9).

The *N*-arylation reactions conditions of *p*-nitrchlorobenzene with imidazole were screened, and the results are shown in Table 1. To optimize the reaction conditions, various bases and solvents were investigated in the presence of copper(I) complex **2** (1 mol%) at 120 ºC for 12 h. The effect of solvent on the coupling was first examined. When single-solvent system (DMF or acetonitrile) was used, moderate yields were obtained (80% and 70%, respectively) (entries 1 and 2). But, when 1,4-dioxane was used as solvent, only 3% yield was obtained (entry 3). Mixed solvents of H_2O with DMF gave lower yields, 10-40% (entries 4-6). Therefore, with DMF as solvent and K_2CO_3 as base, the highest yield was obtained (entry 1). The effect of different bases was also investigated and Cs_2CO_3 gave the best result (entries 7-11). In addition, a blank experiment has been carried out in order to clarify the role of copper. The result showed that only 60% yield was obtained in the absence of complex **2** (entry 12).

Table 1. Optimization of the Ullmann coupling reactions of *p*-nitrchlorobenzene with imidazole. [a, c]



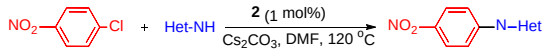
3A **4a** **5Aa**

entry	base	solvent	yield (%)[c]
1	K_2CO_3	DMF	80
2	K_2CO_3	acetonitrile	70
3	K_2CO_3	1,4-dioxane	3
4	K_2CO_3	DMF/H_2O=2:1	10
5	K_2CO_3	DMF/H_2O=5:1	20
6	K_2CO_3	DMF/H_2O=10:1	40
7[b]	Cs_2CO_3	DMF	98
8	K_3PO_4	DMF	25
9	NaOH	DMF	65
10	KOH	DMF	70
11	*t*-BuOK	DMF	10
12[d]	Cs_2CO_3	DMF	60

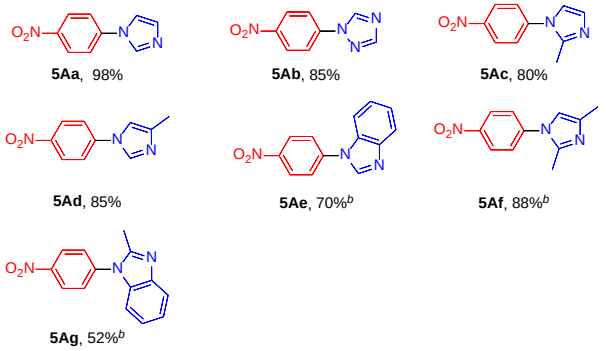
[a] Reactions were carried out using *p*-nitrchlorobenzene (0.2 mmol, 1 equiv), imidazole (0.24 mmol, 1.2 equiv), **2** (0.002 mmol), base (0.4 mmol, 2 equiv) in 0.4 mL solvent at 120 ºC for 12 h. [b] Reaction was carried out for 0.5 h. [c] Isolated yields. [d] Reaction was carried out for 0.5 h in the absence of complex **2**.

With the optimized conditions in hand, we started to explore the substrate scope of the reaction. Representative *p*-nitrchlorobenzene (**3A**) was chosen to react with various N(H)-heterocycles (**4**) (Table 2). The reaction proceeded smoothly with imidazole and an excellent yield (98%) was obtained. For 1,2,4-triazole and 4-methylimidazole, the reaction provided the expected products **5Ab** and **5Ad** in high yield (85%). We were pleased to discover that for hindered 2-methylimidazole also could be coupled with *p*-nitrchlorobenzene in a good yield (80%). Meanwhile, for high sterically hindered benzimidazole, 2,4-dimethylimidazole and 2-methylbenzimidazole, the desired products (**5Ae, 5Af** and **5Ag)** were obtained respectively in 70%, 88%, and 52% yields when the reaction time was delayed to 24 h.

Table 2. Catalytic activities of complex **2** in the *N*-arylation reactions of *p*-nitrchlorobenzene with azoles under the optimized conditions. [a, c]



3A **4a-g** **5**



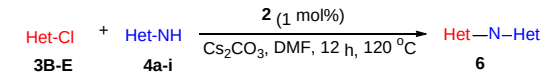
5Aa, 98% **5Ab**, 85% **5Ac**, 80%

5Ad, 85% **5Ae**, 70%[b] **5Af**, 88%[b]

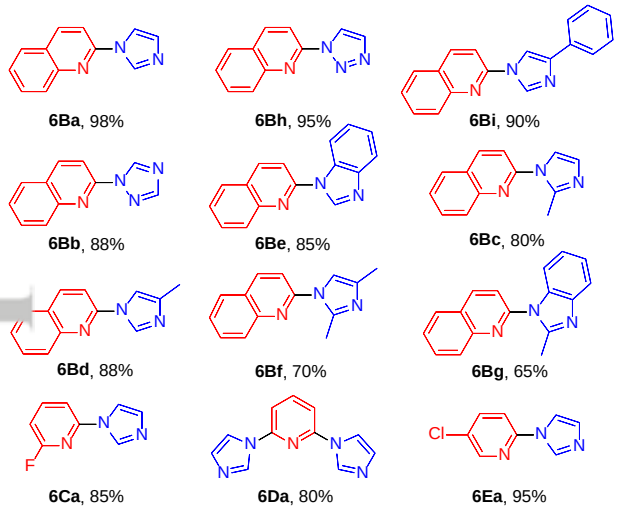
5Ag, 52%[b]

[a] Reactions were carried out using *p*-nitrchlorobenzene (0.2 mmol, 1 equiv), azoles (0.24 mmol, 1.2 equiv), **2** (0.002 mmol), Cs_2CO_3 (0.4 mmol, 2 equiv) in 0.4 mL DMF at 120 °C for 12 h. [b] Reactions were carried out 24 h. [c] Isolated yields.

Table 3. Catalytic activities of complex **2** in the *N*-arylation reactions of heteroaryl chlorides with azoles under the optimized conditions. [a, b]



3B-E **4a-i** **6**



6Ba, 98% **6Bh**, 95% **6Bi**, 90%

6Bb, 88% **6Be**, 85% **6Bc**, 80%

6Bd, 88% **6Bf**, 70% **6Bg**, 65%

6Ca, 85% **6Da**, 80% **6Ea**, 95%

[a] Reactions were carried out using heteroaryl chlorides (0.2 mmol, 1 equiv), azoles (0.24 mmol, 1.2 equiv), **2** (0.002 mmol), Cs_2CO_3 (0.4 mmol, 2 equiv) in 0.4 mL DMF at 120 °C for 12 h. [b] Isolated yields.

Encouraged by the above results, the coupling reactions of a variety of heteroaryl chlorides with azoles under the optimized conditions were also investigated and the results were outlined in Table 3. It is notable that the coupling of 2-chloroquinoline with imidazole, 1,2,3-triazole and 4-phenylimidazole worked well, affording the desired products (**6Ba, 6Bh and 6Bi**) in high to excellent yields (98%, 95% and 90%, respectively). The others N(H)-heterocycles substrates, including 1,2,4-triazole, benzimidazole, hindered 2-methylimidazole and 4-methylimidazole, also could couple with 2-chloroquinoline and afforded the coupling products in good to high yields (80-88%). 2,4-Dimethylimidazole and 2-methylbenzimidazole gave moderate yields (70% and 65%, respectively). When 2-chloroquinoline was replaced by 2-chloropyridine derivatives with different functional groups, such as 2-chloro-6-fluoropyridine, 2,6-dichloropyridine, or 2,5-dichloropyridine, they also successfully completed the coupling with imidazole. The corresponding *N*-arylated products (**6Ca**, **6Da** and **6Ea**, respactively) were also prepared in high to excellent yields (85%, 80% and 95%, respectively).

Conclusions

In summary, a new N-heterocyclic carbene copper(I) complex has been synthesized and used in the *N*-arylation of (hetero)aryl chlorides and nitrogen heterocycles. With a low catalyst loading (1 mol %), both (hetero)aryl chlorides and N(H)-heterocycles performed very well and a series of heteroarylazole derivatives with high to excellent yields were obtained, which could be used for the further preparation of industrially and pharmaceutically important compounds. This new catalytic system provided an important theoretical basis for the design of other catalytic systems.

Experimental

Reagents and general techniques. Unless otherwise noted, all reactions were performed under an atmosphere of dry N_2 with oven-dried glassware and anhydrous solvents. The reagents were obtained from commercial sources and used directly. 1,8-Naphthyrido[1,2-a]-(2′,6′-diisopropylphenyl)limidazolium chloride **1** was synthesized according to reference. [17]

Preparation of Cu(I)-NHC Complex 2: A suspension of CuCl (14.3 mg, 0.144 mmol), K_2CO_3 (35.8 mg, 0.260 mmol) and limidazolium chloride **1** (34.9 mg, 0.096 mmol) in dry acetone (2 mL) was heated at 60 °C for 24 h under a N_2 atmosphere. After cooling to room temperature, the solution was filtered and the solvent was removed in vacuum. The residue was dissolved in CH_2Cl_2, and then petroleum ether was added. The mixture was filtered and the resulting yellow solid was washed with petroleum ether and dried under vacuum. Yield: 60% (24.8 mg, 0.058 mmol). Yellow solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 8.80 (s, 1H), 8.13 (d, *J* = 4.0 Hz, 1H), 7.59-7.52 (m, 2H), 7.43-7.33 (m, 5H), 2.41 (m, 2H), 1.31 (d, *J* = 8.0 Hz, 6H), 1.18 (d, *J* = 8.0 Hz, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm): 173.2, 147.8, 145.1, 144.5, 137.1, 135.4, 130.1, 129.2, 123.8, 123.2, 118.9, 116.9, 116.7, 28.1, 24.5, 24.0. Anal. Calcd for C22H23ClCuN3: C, 61.67; H, 5.41; N, 9.81. Found: C, 61.17; H, 5.38; N, 9.78.

General Procedure for Cu(I)-NHC Catalyzed *N*-arylation of (hetero)aryl chlorides with nitrogen heterocycles:

A test tube was charged with (hetero)aryl chlorides (0.2 mmol, 1 eq), nitrogen heterocycles (0.24 mmol, 1.2 eq), Cs_2CO_3 (0.4 mmol, 2 eq), DMF (0.4 mL) and complex **2** (0.002 mmol). The

mixture was heated at 120 °C for 12 h (or 24 h). After the reaction was completed, the reaction mixture was cooled to room temperature, diluted with dichloromethane (2 mL), washed with water (3 x 2 mL). After removing the solvent under vacuum, the resulting residue was purified by flash chromatography using a mixture of hexane and ethyl acetate to provide the desired products.

1-(4-Nitro-phenyl)-1H-imidazole (5Aa): [13e] Yellow solid. Yield: 98%. ^{1}H NMR (400 MHz, DMSO) δ (ppm): 8.49 (s, 1H), 8.34 (d, *J* = 12.0 Hz, 2H), 7.96 (d, *J* = 8.0 Hz, 2H), 7.93 (s, 1H), 7.18 (s, 1H). ^{13}C NMR (100 MHz, DMSO) δ (ppm): 145.3, 141.8, 136.1, 130.9, 125.6, 120.4, 118.0.

1-(4-Nitro-phenyl)-1H-[1,2,4]triazole (5Ab): [18] White solid. Yield: 85%. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 8.71 (s, 1H), 8.40 (d, *J* = 8.0 Hz, 2H), 8.16 (s, 1H), 7.92 (d, *J* = 8.0 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm): 153.5, 146.8, 141.3, 125.6, 119.9.

2-Methyl-1-(4-nitro-phenyl)-1H-imidazole (5Ac): [13i] Yellow solid. Yield: 80%. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 8.34 (d, *J* = 12.0 Hz, 2H), 7.88 (s, 1H), 7.52 (d, *J* = 8.0 Hz, 2H), 7.09 (s, 1H), 2.29 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm): 145.8, 142.0, 141.0, 134.4, 125.7, 120.3, 113.8, 13.7.

4-Methyl-1-(4-nitro-phenyl)-1H-imidazole (5Ad): Yellow solid. Yield: 85%, mp 144-146 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 8.32 (d, *J* = 8.0 Hz, 2H), 7.87 (s, 1H), 7.52 (d, *J* = 12.0 Hz, 2H), 7.08 (s, 1H), 2.28 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm): 145.7, 142.0, 141.0, 134.4, 125.6, 120.3, 113.8, 13.6. Anal. Calcd for C10H9N3O2: C, 59.11; H, 4.46; N, 20.68. Found: C, 59.37; H, 4.52; N, 20.55.

1-(4-Nitro-phenyl)-1H-benzoimidazole (5Ae): [18] Yellow solid. Yield: 70%. ^{1}H NMR (400 MHz, DMSO) δ (ppm): 8.72 (s, 1H), 8.42 (d, *J* = 12.0 Hz, 2H), 7.99 (d, *J* = 8.0 Hz, 2H), 7.80 (d, *J* = 8.0 Hz, 1H), 7.74 (d, *J* = 8.0 Hz, 1H), 7.39-7.32 (m, 2H). ^{13}C NMR (100 MHz, DMSO) δ (ppm): 145.7, 144.2, 143.3, 141.4, 132.4, 125.6, 124.1, 123.7, 123.2, 120.3, 111.0.

2,4-Dimethyl-1-(4-nitro-phenyl)-1H-imidazole (5Af): Yellow solid. Yield: 88%, mp 184-186 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 8.34 (d, *J* = 8.0 Hz, 2H), 7.46 (d, *J* = 12.0 Hz, 2H), 6.78 (s, 1H), 2.40 (s, 3H), 2.23 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm): 146.4, 143.6, 143.2, 137.8, 125.7, 125.3, 125.0, 120.3, 116.3, 14.1, 13.3. Anal. Calcd for C11H11N3O2: C, 60.82; H, 5.10; N, 19.34. Found: C, 60.77; H, 5.09; N, 19.29.

2-Methyl-1-(4-nitro-phenyl)-1H-benzoimidazole (5Ag): Yellow solid. Yield: 52%, mp 226-228 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 8.48 (d, *J* = 12.0 Hz, 2H), 7.77 (d, *J* = 8.0 Hz, 1H), 7.62 (d, *J* = 8.0 Hz, 2H), 7.34-7.24 (m, 2H), 7.18 (d, *J* = 8.0 Hz, 1H), 2.58 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm): 150.7, 147.2, 142.7, 141.6, 135.5, 127.5, 125.4, 123.2, 123.1, 119.4, 109.5, 14.6. Anal. Calcd for C14H11N3O2: C, 66.40; H, 4.38; N, 16.59. Found: C, 66.32; H, 4.27; N, 16.61.

2-Imidazol-1-yl-quinoline (6Ba): [4g] White solid. Yield: 98%. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 8.49 (s, 1H), 8.25 (d, *J* = 8.0 Hz, 1H), 8.01 (d, *J* = 8.0 Hz, 1H), 7.82-7.80 (m, 2H), 7.76-7.71 (m, 1H), 7.54-7.51 (m, 1H), 7.48 (d, *J* = 8.0 Hz, 1H), 7.24 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm): 146.8, 139.5, 130.7, 128.6, 127.5, 126.8, 126.4, 111.6.

2-[1,2,3]Triazol-1-yl-quinoline (6Bh): [19] Yellow solid. Yield: 95%. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 8.82 (s, 1H), 8.37 (s, 2H), 8.06 (d, *J* = 12.0 Hz, 1H), 7.89 (d, *J* = 8.0 Hz, 2H), 7.78 (t, *J* = 8.0 Hz, 1H), 7.59 (t, *J* = 8.0 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm): 147.9, 146.4, 139.6, 134.3, 130.7, 128.9, 127.9, 127.8, 127.1, 121.2, 112.7.

2-(4-Phenyl-imidazol-1-yl)-quinoline (6Bi): Yellow solid. Yield: 90%, mp 154-156 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 8.49 (s, 1H), 8.23 (d, *J* = 8.0 Hz, 1H), 8.12 (s, 1H), 8.02 (d, *J* = 8.0 Hz, 1H), 7.90 (d, *J* = 8.0 Hz, 2H), 7.80 (d, *J* = 8.0 Hz, 1H), 7.74 (t, *J* = 8.0 Hz, 1H), 7.53-7.47 (m, 2H), 7.42 (t, *J* = 8.0 Hz, 2H), 7.29 (t, *J* = 8.0 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm): 147.1, 146.8, 143.2, 139.5, 135.1, 133.4, 130.7, 128.6, 128.5, 127.5, 127.2, 126.8, 126.4, 125.0, 111.6, 111.3. Anal. Calcd for C18H13N3: C, 79.68; H, 4.83; N, 15.49. Found: C, 79.71; H, 4.69; N, 15.61.

2-[1,2,4]Triazol-1-yl-quinoline (6Bb): [19] White solid. Yield: 88%. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 9.34 (s, 1H), 8.27 (d, *J* = 8.0 Hz, 1H), 8.12 (s, 1H), 8.03-7.97 (m, 2H), 7.81 (d, *J* = 8.0 Hz, 1H), 7.74-7.70 (m, 1H), 7.54-7.50 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm): 152.6, 147.7, 146.0, 141.6, 139.4, 130.5, 128.4, 127.5, 127.3, 126.6, 111.9.

2-Benzoimidazol-1-yl-quinoline (6Be): [19] Yellow solid. Yield: 85%. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 8.68 (s, 1H), 8.42 (d, *J* = 8.0 Hz, 1H), 8.14 (d, *J* = 12.0 Hz, 1H), 8.06 (d, *J* = 8.0 Hz, 1H), 7.98 (d, *J* = 8.0 Hz, 1H), 7.75-7.71 (m, 2H), 7.51-7.45 (m, 4H). ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm): 148.0, 146.5, 144.3, 140.8, 138.8, 131.8, 130.2, 128.1, 127.1, 125.9, 124.0, 123.1, 120.1, 113.7, 112.2.

2-(2-Methyl-imidazol-1-yl)-quinoline (6Bc): Yellow solid. Yield: 80%, mp 68-70 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 8.27 (d, *J* = 8.0 Hz, 1H), 8.03 (d, *J* = 8.0 Hz, 1H), 7.84 (d, *J* = 8.0 Hz, 1H), 7.77-7.73 (m, 1H), 7.58-7.54 (m, 1H), 7.43 (d, *J* = 12.0 Hz, 1H), 7.39 (d, *J* = 4.0 Hz, 1H), 7.06 (d, *J* = 4.0 Hz, 1H), 2.71 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm): 149.2, 146.7, 145.3, 139.1, 130.5, 128.8, 128.0, 127.4, 126.8, 126.5, 118.7, 115.4, 15.7. Anal. Calcd for C13H11N3: C, 74.62; H, 5.30; N, 20.08. Found: C, 74.66; H, 5.37; N, 19.98.

2-(4-Methyl-imidazol-1-yl)-quinoline (6Bd): Yellow solid. Yield: 88%, mp 90-92 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 8.40 (s, 1H), 8.23 (d, *J* = 12.0 Hz, 1H), 7.99 (d, *J* = 8.0 Hz, 1H), 7.79 (d, *J* = 8.0 Hz, 1H), 7.74-7.70 (m, 1H), 7.55 (s, 1H), 7.52-7.49 (m, 1H), 7.43 (d, *J* = 8.0 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm): 147.5, 146.9, 139.4, 130.6, 128.6, 127.5, 126.7, 126.2, 111.5, 13.7. Anal. Calcd for C13H11N3: C, 74.62; H, 5.30; N, 20.08. Found: C, 74.71; H, 5.31; N, 20.00.

2-(2,4-Dimethyl-imidazol-1-yl)-quinoline (6Bf): Yellow solid. Yield: 70%, mp 95-97 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 8.26 (d, *J* = 8.0 Hz, 1H), 8.03 (d, *J* = 8.0 Hz, 1H), 7.84 (d, *J* = 8.0 Hz, 1H), 7.77-7.73 (m, 1H), 7.58-7.54 (m, 1H), 7.41 (d, *J* = 8.0 Hz, 1H), 7.12 (s, 1H), 2.69 (s, 3H), 2.26 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm): 149.3, 146.9, 144.7, 139.0, 137.0, 130.5, 128.8, 127.4, 126.7, 126.5, 115.4, 114.8, 15.8, 13.4. Anal. Calcd for C14H13N3: C, 75.31; H, 5.87; N, 18.82. Found: C, 75.24; H, 5.86; N, 18.92.

2-(2-Methyl-benzoimidazol-1-yl)-quinoline (6Bg): Yellow solid. Yield: 65%, mp 365-367 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 8.39 (d, *J* = 8.0 Hz, 1H), 8.12 (d, *J* = 8.0 Hz, 1H), 7.93 (d, *J* = 8.0Hz, 1H), 7.83-7.79 (m, 1H), 7.77 (d, *J* = 8.0 Hz, 1H) 7.66-7.62 (m, 1H), 7.59 (d, *J* = 12.0 Hz, 1H), 7.48 (d, *J* = 8.0 Hz, 1H), 7.32-7.22 (m, 2H), 2.77 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm): 149.2, 146.7,

145.3, 139.1, 130.5, 128.8, 128.7, 128.0, 127.4, 126.8, 126.5, 118.7, 115.4, 15.7. Anal. Calcd for C17H13N3: C, 78.74; H, 5.05; N, 16.20. Found: C, 78.76; H, 5.01; N,16.17.

2-Fluoro-6-imidazol-1-yl-pyridine (6Ca): [20] Yellow solid. Yield: 85%. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 8.36 (s, 1H), 7.81 (t, *J* = 8.0 Hz, 1H), 7.65 (s, 1H), 7.32-7.28 (m, 2H), 7.22 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm): 150.6, 148.6, 141.2, 134.9, 130.9, 122.1, 116.0, 110.2. ^{19}F NMR (376 MHz, $CDCl_3$) δ (ppm): -66.20.

2,6-Di-imidazol-1-yl-pyridine (6Da): [20] Yellow solid. Yield: 80%. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 8.41 (s, 2H), 8.00 (t, *J* = 8.0 Hz, 1H), 7.70 (s, 2H), 7.32 (d, *J* = 8.0 Hz, 2H), 7.26 (s, 2H). ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm): 148.2, 142.0, 134.9, 131.0, 116.0, 109.5.

5-Chloro-2-imidazol-1-yl-pyridine (6Ea): Yellow solid. Yield: 95%, mp 127-129 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 8.39 (d, *J* = 2.3 Hz, 1H), 8.28 (s, 1H), 7.76 (dd, *J* = 8.7 Hz, 2.5 Hz, 1H), 7.56 (s, 1H), 7.29 (d, *J* = 8.0 Hz, 1H), 7.17 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm): 147.7, 147.2, 138.6, 134.8, 130.8, 129.5, 116.0, 112.9. Anal. Calcd for C8H6ClN3: C, 53.50; H, 3.37; N, 23.40. Found: C, 53.71; H, 3.27; N, 23.32.

Supporting Information

NMR spectra of complex **2** and all products. CCDC 1964792 contain the supplementary crystallographic data for complex **2**. This data can be obtained free of charge via http://www.ccdc.cam.ac.uk/conts/retrieving.html, or from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: (+44) 1223-336-033; or e-mail: deposit@ccdc.cam.ac.uk.

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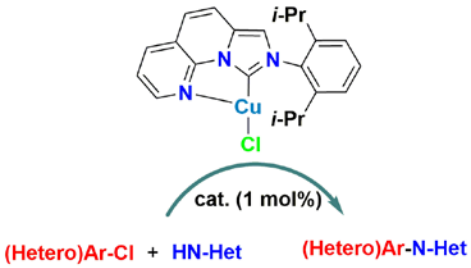
N-Heterocyclic Carbene Copper(I) Complex Catalyzed Coupling of (Hetero)aryl Chlorides and Nitrogen Heterocycles: Highly Efficient Catalytic System



Mengyao Zhang, Yingying Zhang, Huixin Zhang, Yongfei Zeng*, Guiyan Liu*

A highly efficient NHC-copper(I) complex was developed. The structure of this NHC-copper(I) complex has been determined by X-ray crystallography. This NHC-copper(I) complex was found to be efficient for the *N*-arylation reactions of (hetero)aryl chlorides and nitrogen Heterocycles with low catalyst loading.

