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Highly Efficient C—N Bond Forming Reactions in Water Catalyzed by Copper(I) Iodide with Calix[4]arene Supported Amino Acid Ionic Liquid

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A novel and effective protocol has been developed for the Ullmann-type C—N coupling reaction catalyzed by calix[4]arene supported amino acid ionic liquid and copper(I) iodide in water under microwave irradiation condition. The protocol uses calix[4]arene supported amino acid ionic liquid as double function of the ligand and phase-transfer catalyst, and shows good tolerance in good to excellent yields.

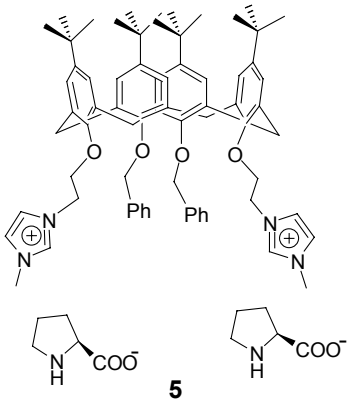
Keywords calix[4]arene supported ionic liquid, copper(I) iodide, surfactant, cross-coupling, microwave irradiation

Introduction

Ullmann-type C—N coupling reaction is an important way to synthesize nitrogen-containing heterocycles, which are widely employed building blocks for the synthesis of pharmaceutical and natural products.[1] Although the copper catalyzed Ullmann-type C—N coupling reaction is a straightforward and inexpensive approach, here are some disadvantages, such as high reaction temperatures (generally 140 ℃ or higher), long reaction time (24—60 h), the requirement of strong bases and the need of a stoichiometric amount of copper catalyst.[2] These facts and the moderate products yields limit the synthetic utility of this method. In the past few decades, more and more attentions have been paid to the improvement of the classical Ullmann chemistry.[3] DMF,[4] DMSO,[5] NMP,[6] CH_3CN[7] are the common solvent of Ullmann-type coupling. A few papers refer to the procedure for Ullmann-type coupling in water recently,[8] however, inefficient and inadequate mixing of the heterogeneous reaction system limit the development of its synthetic utility in aqueous phase. Our group has been researched on synthesis and application of calix[4]arene derivatives, on this basis, we attempted to design a novel catalytic system for the assembly of *N*-arylated nitrogen-containing heterocycles in water.

Results and Discussion

Herein, we described the design and use of novel calix[4]arene supported amino acid ionic liquid catalyst possessing both an [Emim][Pro] catalytic center and a calix[4]arene skeleton for the direct aqueous Ullmann-type C—N coupling reaction. On that basis, we tried to complete this reaction by microwave irradiation with a main purpose of more quick rates and more undivided selectivities.[8a] The structure of the [Emim][Pro] based on the calix[4]arene scaffold **5** is shown in Figure 1.



5

Figure 1 Structure of calix[4]arene [Emim][Pro] **5**.

We described that calix[4]arene supported amino acid ionic liquids could be used as both ligand and surfactant in the Ullmann C—N coupling reaction with aqueous solvent. The functional group [Emim][Pro] was designed as ligand and hydrophilic functions, simultaneously, the calix[4]arene bearing pendant aryl chains were devised as hydrophobic function. In order to control Hydrophilic Lipophilic Balance[9] (HLB), **5** was synthesized as the

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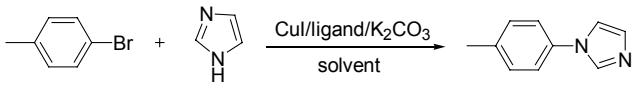
ligand and phase transfer catalyst.

Calix[4]arene [Emim][Pro] **5** can be prepared from the already reported *p*-*t*-butyl-25,27-bis-*O*-(2-bromoethoxy) calix[4]arene (**2**).[10] The process is outlined in Scheme 1. Treatment of **2** with benzyl bromide in the presence of LiH gave compound **3** in cone conformation. **3** was transformed into intermediate **4** by treatment with 10 equiv. of 1-methyl-1*H*-imidazole. Then, calix[4]arene imidazolium hydroxide could easily be obtained by an anion exchange reaction of **4** with 201×7 Styrene-DVB. Lastly, *L*-proline was used to neutralize calix[4]arene imidazolium hydroxide and gave the objective product **5** which was confirmed by ^{1}H and ^{13}C NMR spectra, and ESI-MS spectrometry.

As we know, *L*-proline is an effective catalyst and ligand in many types of reaction, such as asymmetric Michael addition, aza-Diels-Alder cyclization, Ullmann coupling reaction, and so on.[11] However, it has never been reported for synthesis and application of calix[4]-arene-[Emim][Pro].

A preliminary survey of reaction conditions was conducted using 1-bromo-4-methylbenzene and imidazole as model arylating substrate (Table 1, Entries 1—8). As shown in Table 1, the best result was obtained in H_2O at 140 ℃ for 10 min under microwave irradiation and N_2 atmosphere, using 2.4 equiv. of K_2CO_3 as the base in the presence of a catalyst system generated from 10 mol% of CuI and 10 mol% of **5** (Table 1, Entry 3). Compared with TBAB,[8b] **5** has higher catalytic performance in water: 1-bromo-4-methylbenzene could be activated by **5** to react with imidazole to afford 95% of the corresponding product, however, the yield was only 40% when TBAB was used (compare Entry 3 to Entry 9). We suspected that the suitable HLB of **5** resulted in the well water-solubility and the micellar effects,[12] simultaneously, *L*-proline played an important role[5a] in the function of ligand. To prove that both the *L*-proline and the calix[4]arene skeleton on **5** were the same important groups in the aqueous phase Ullmann coupling reaction, we used *L*-proline or **3** separately as ligand. It was confirmed that there was hardly any response to this reaction in water with **3** or *L*-proline respectively (Table 1, Entries 4 and 8). To compare the reaction method, CuI/**5** (10 mol%)/K_2CO_3/H_2O was used as the reaction system, this Ullmann coupling reaction was performed under conven-

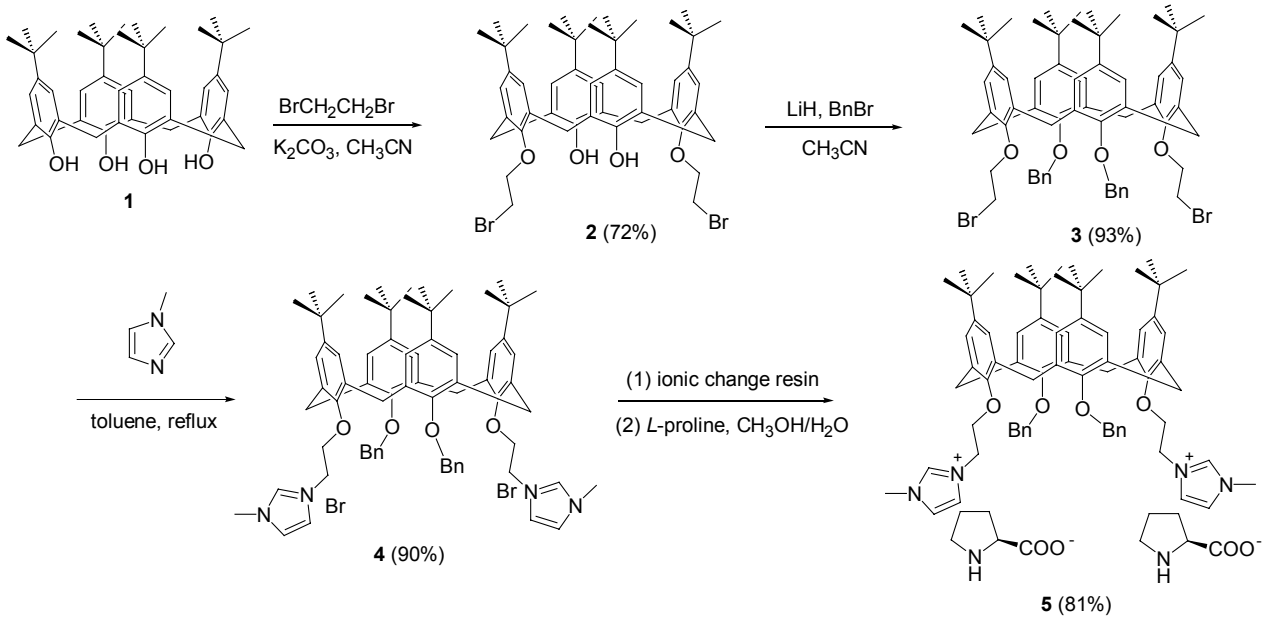
Table 1 Some representative results from the screening of reaction conditions for the *N*-arylation of imidazole with 1-bromo-4-methylbenzene[a]



Entry	Ligand/mol%	Solvent	Time/min	Yield[b]/%
1[c]	**5** (10)	H_2O	48 h	85
2	**5** (5)	H_2O	10	15
3	**5** (10)	H_2O	10	95
4	*L*-Pro (20)	H_2O	10	Trace
5	*L*-Pro (20)	DMF	10	50
6	**5** (10)	DMF	5	72
7[d]	**5** (10)	DMSO	48 h	80
8	**3** (10)	H_2O	10	Trace
9	TBAB (10)	H_2O	10	40

[a] CuI (9.5 mg, 0.05 mmol), ligand, K_2CO_3 (165 mg, 1.2 mmol), imidazole (0.5 mmol), 1-bromo-4-methylbenzene (0.6 mmol), and H_2O (2 mL) under N_2, microwave irradiation under 140 ℃. [b] Isolated yields based on imidazole. [c] Traditional heating under 85 ℃ for 48 h. [d] Traditional heating under 120 ℃ for 48 h.

Scheme 1 Synthesis of the calix[4]arene [Emim][Pro] **5**



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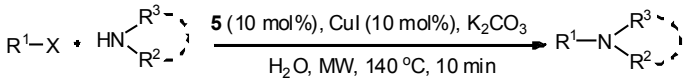
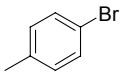
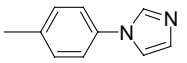
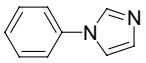
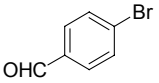
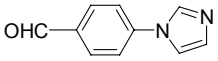
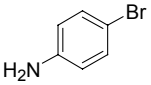
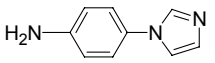
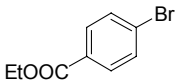
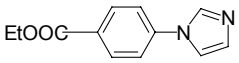
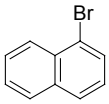
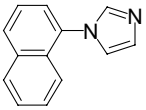
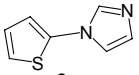
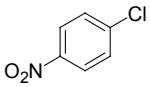
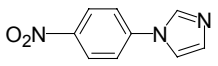
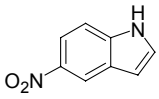
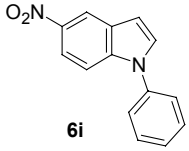
tional heating condition at 85 ℃ for 48 h, giving 85% yield (Table 1, Entry 1). It illustrated that the method of microwave condition has a higher efficiency than conventional heating. When DMF was chosen as the solvent under microwave condition, only 72% of the corresponding product was obtained (Table 1, Entry 6). The reason for lower yield was that DMF was easily decomposed under microwave heating condition.

Inspired by these results, we decided to focus on the scope of the reaction by the standard reaction condition. We were delighted to find that the *N*-arylation of imidazole with a broad range of aryl or heteroaryl bromides could be conducted smoothly to afford the corresponding products in good to excellent yields (Table 2, Entries 1—7). Notably, our catalyst system showed very high activity with electron-deficient aryl chloride (Table 2, Entries 8). It is more interesting that the substrates that contain certain functional groups (for example ester, carbonyl, amido and nitro), could be sustained in our catalytic system and reaction condition (Table 2, Entries 3—5, 7). To our knowledge, the substrates that contain certain functional groups always have some problem in the *N*-arylation of imidazoles. Only a few literatures had reported the reaction previously.[13]

Table 2 Microwave-assisted CuI/**5** catalyzed coupling reactions of aryl halides with anilines in water[a]



Entry	R[1]—X	Amines	Products	Yield[b]/%
1			 **6a**	95 93, 91, 90[c]
2			 **6b**	87
3			 **6c**	85
4			 **6d**	85
5			 **6e**	91
6			 **6f**	75
7			 **6g**	94
8[d]			 **6h**	98
9			 **6i**	97

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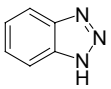
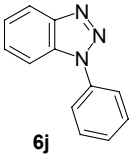
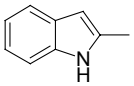
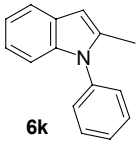
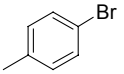
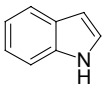
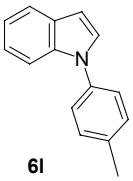
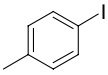
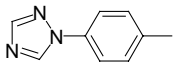
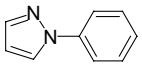
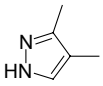
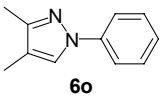
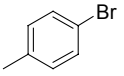
Continued

Entry	R^1—X	Amines	Products	Yield[b]/%
10			 **6j**	95
11			 **6k**	77
12			 **6l**	90
13			 **6m**	96
14			 **6n**	92
15			 **6o**	73
16			—	Trace

[a] CuI (9.5 mg, 0.05 mmol), K_2CO_3 (165 mg, 1.2 mmol), **5** (51 mg, 0.05 mmol), imidazole (0.5 mmol), aryl halides (0.6 mmol), and H_2O (2 mL) under N_2, microwave irradiation under 140 ℃ for 10 min. [b] Isolated yields based on imidazole. [c] Recycle first, second, third time. [d] Microwave irradiation under 100 ℃ for 15 min.

On the other hand, our catalytic system and reaction condition showed high activity and an extensive structural range of other nitrogen heterocycles. To our delight, the π-electron-deficient nitrogen heterocycles showed higher activity in our protocol (Table 2, Entries 9 and 10). However, π-electron-rich nitrogen heterocycles such as 2-methyl-1*H*-indole and 3,4-dimethyl-1*H*-pyrazole were proved to be less reactive (Table 2, Entries 11 and 15). It is worthy to indicate that the reaction of 1*H*-1,2,4-triazole and 1-iodo-4-methyl benzene could be in the process successfully, and give an excellent yield (Table 2, Entry 13). But no reaction forwarded when 1-iodo-4-methylbenzene was replaced by 1-bromo-4-methylbenzene (Table 2, Entry 16).

A variety of nitrogen heterocycles could be *N*-arylated with aryl or heteroaryl halides effectively under the corresponding experimental conditions. It is reasonable that the significantly enhanced catalytic activity may stem from high micellar effects[14] between **5** and water. Consequently, **5** that played the role of phase transfer catalyst and ligand simultaneously had an important effect in the catalytic system. Further, the catalytic activity of **5** did not show significant decrease after being reused three times (Table 2, Entry 1).

Conclusions

In summary, A novel calix[4]arene [Emim][Pro] (**5**) was prepared successfully as the supported ionic liquid catalysis primarily. The Ullmann-type C—N coupling reaction was proceeded smoothly by using the catalytic system of CuI/**5**/K_2CO_3 in water under microwave irradiation to afford the corresponding products in good to excellent yields. The catalytic activity of **5** did not show significant decrease after being reused three times. In addition, effects are in progress to extend to other applications of calix[4]arene [Emim][Pro] as surfactant and ligand.

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Experimental

General methods

All the reagents were from commercial sources. All microwave irradiation experiments were carried out in a Discover-CEM mono mode microwave apparatus. Melting points (m.p.) were recorded on a WRS-1B digital melting point apparatus and uncorrected. ^{1}H NMR and ^{13}C NMR spectra were obtained on a Varian Mercury plus-400 spectrometer using $CDCl_3$ as the solvent with TMS as the internal standard. Mass spectra were measured with a Finnigan Trace DSQ spectrometer. IR spectra were recorded using KBr pellets on a Nicolet Aviatar-370 instrument. Mass spectra were measured with Thermo Finnigan LCQ-Advantage. High resolution mass spectral (HRMS) analysis was performed on a Bruker micrOTOF-QⅡ using ESI techniques.

Experimental procedure and physical data

p-t-Butyl-25,27-bis-*O*-(2-bromoethoxy)calix[4]-arene (**2**): *p-t*-Butyl-calix[4]arene (**1**) (1.0 g, 1.5 mmol), K_2CO_3 (2.07 g, 15 mmol) were dissolved under nitrogen in CH_3CN (100 mL) for 30 min. Then 1,2-dibromoethane (8.7 g, 46 mmol) was added and the mixture was stirred under nitrogen at 80 ℃ for 10 h. After quenched with aqueous HCl (20 mL), the mixture was stirred for ten more minutes. After the removal of CH_3CN by evaporation, the aqueous layer was extracted with CH_2Cl_2 (30 mL×3). The organic layer was then washed with brine (30 mL) and H_2O (20×2 mL), dried over Na_2SO_4, filtrated and evaporated. The obtained solid was dissolved in ethyl acetate (20 mL), filtrated off. The filtrate was evaporated to give crude product that was purified by recrystallisation in CH_2Cl_2/MeOH (1∶5) to give **2**. (0.74 g, 72%) as white crystal: m.p. 277—280 ℃ [Lit.[15] m.p. 278—280 ℃]; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.04 (s, 4H), 6.93 (s, 2H), 6.77 (s, 4H), 4.35—4.25 (m, 8H), 3.83 (t, J=6.4 Hz, 4H), 3.32 (d, J=13.0 Hz, 4H), 1.29 (s, 18H), 0.95 (s, 18H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 150.3, 149.1, 147.0, 141.4, 132.2, 127.5, 125.5, 125.0, 75.3, 34.0, 33.9, 31.8, 31.0, 29.4; MS (ESI) *m/z*: 885.4 ($M+Na^+$).

p-t-Butyl-25,27-bis-*O*-(2-bromoethoxy)-26,28-bis-*O*-benzyloxycalix[4]arene (**3**): To a solution of *p-t*-butyl-25,27-bis(2-bromoethoxy)calix[4]arene (**2**) (11.2 g, 13.0 mmol) and LiH (1 g, 130 mmol, 98% content) in CH_3CN (300 mL) was added benzyl bromide (22.2 g, 130 mmol) at room temperature. The reaction mixture was stirred for 2 h at room temperature and then quenched with aqueous HCl (150 mL). After the removal of CH_3CN by evaporation, organic materials were extracted with CH_2Cl_2 (70 mL×3) and the organic extracts were dried with $MgSO_4$. Evaporation of solvents and purification of the residue by recrystallization with CH_2Cl_2/MeOH afforded **3** (9.4 g, 83%) as white crystal: m.p. 242—243 ℃; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.04 (s, 4H), 6.94 (s, 2H), 6.77 (s, 4H), 4.34—4.25 (m, 8H), 3.83 (t, J=6.4 Hz, 4H), 3.32 (d, J=13.1 Hz, 4H), 1.29 (s, 18H), 0.95 (s, 18H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 153.5, 151.6, 145.5, 144.5, 136.8, 135.1, 131.6, 129.4, 128.7, 128.4, 125.5, 124.5, 78.6, 73.6, 34.2, 33.7, 31.8, 31.3, 31.2, 29.5; IR ν_{max}: 2961, 1480, 1202, 1122, 1010, 993, 697 cm^{-1}; MS (ESI) *m/z*: 1060.6 ($M+NH_4^+$). HRMS (ESI) calcd for $C_{62}H_{78}Br_2NO_4^+$ [$M+NH_4^+$]: 1060.4277, found 1060.4271.

Calix[4]arene supported [Emim][Br] (**4**): A mixture of 1-methyl-1*H*-imidazole (0.79 g, 9.6 mmol) with **3** (0.51 g, 0.48 mmol) in toluene (5 mL) was stirred at 100 ℃ for 11 h. After cooling the reaction mixture to room temperature, the suspension was filtered off and the solid dissolved in MeOH (30 mL). The solvent was then distilled off, and the solid residue was recrystallized with CH_2Cl_2/CH_3OH (5∶1) to afford **4** (0.52 g, 90%) as white solid: m.p. 285—286 ℃; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 9.43 (s, 1H), 7.57 (d, J=11.2 Hz, 2H), 7.46—7.32 (m, 8H), 7.29—7.20 (m, 3H), 7.09 (s, 4H), 6.74 (s, 2H), 6.41 (s, 4H), 4.79 (s, 4H), 4.67 (t, J=7.2 Hz, 4H), 4.36 (t, J=6.5 Hz, 4H), 4.17—4.06 (m, 10H), 3.09 (d, J=12.8 Hz, 4H), 1.34 (s, 18H), 0.81 (s, 18H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 151.8, 150.9, 146.4, 144.8, 137.0, 136.7, 135.1, 131.3, 129.7, 128.7, 128.1, 125.6, 124.5, 123.5, 121.3, 78.3, 70.3, 48.6, 36.9, 34.2, 33.6, 31.7, 31.2, 31.0; IR ν_{max}: 2960, 1480, 1193, 1174, 1124, 1044 cm^{-1}; MS (ESI) *m/z*: 1127.6 ($M-Br^-$). HRMS (ESI) calcd for $C_{70}H_{86}BrN_4NO_4^+$ [$M-Br^-$]: 1127.5074, found 1127.5768.

Calix[4]arene supported [Emim][Pro] (**5**): The **4** (1.0 g, 0.83 mmol) was stirred with anion ion resin (201×7 Styrene-DVB, 10 equiv. based on the imidazolium group) in MeOH for 40 h at room temperature. The resulting **5** was separated and evaporated, followed by a stirring in MeOH/H_2O (10∶1, 20 mL) of *L*-proline (1 mol/L, 100 equiv. based on the imidazolium group) for 40 h at room temperature. The solution was then added acetonitrile (50 mL), standing stillness for 30 min. The residue was added to acetonitrile, and then filtered through a plug of silica gel. The filter was washed with acetonitrile, and then the filtrate was distilled off. This process was repeated for three times. The resulting residue was dried *in vacuo* for 24 h to afford **5** (0.85 g, 81%) as white solid: m.p. 143.6—145.0 ℃; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.50—7.48 (m, 1H), 7.36—7.35 (m, 4H), 7.30—7.27 (m, 12H), 7.10—7.07 (m, 3H), 6.73—6.71 (m, 1H), 6.43—6.41 (m, 3H), 4.77 (s, 4H), 4.65 (t, J=6.7 Hz, 4H), 4.31 (t, J=6.7 Hz, 4H), 4.18—4.15 (m, 4H), 4.03 (s, 6H), 3.70—3.67 (m, 2H), 3.05—3.04 (m, 5H), 2.93—2.90 (m, 1H), 2.13—2.07 (m, 2H), 1.98 (s, 1H), 1.94—1.86 (m, 2H), 1.73—1.68 (m, 4H), 1.33 (s, 18H), 0.83—0.81 (m, 18H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 152.3, 151.2, 146.6, 145.1, 137.3, 135.2, 131.5, 129.9, 129.7, 128.7, 128.5, 128.3, 128.0, 125.8, 124.7, 123.6, 121.6, 78.3, 77.4, 77.3, 76.8, 70.8, 61.9, 61.4, 48.8, 36.4, 34.2, 33.7, 31.8, 31.7, 31.5, 31.1; IR ν_{max}: 3380, 2960, 1617, 1577, 1480, 1416, 1193 cm^{-1}; MS (ESI) *m/z*: 1160.2 ($M-C_5H_8NO_2^-$), 1388.3 (M+

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$C_5H_8NO_2^-$). HRMS (ESI) calcd for $C_{75}H_{94}N_5O_6^-$ [M—$C_5H_8NO_2^-$]: 1160.7204, found 1160.7210.

Ullmann coupling reaction experimental procedure and physical data

In a 10 mL pressurized vial "snap-on" cap with a magnetic stirring bar was charged with CuI (9.5 mg, 0.05 mmol), calix[4]arene [Emim][Pro] **5** (64 mg, 0.1 mmol of *L*-proline), K_2CO_3 (165 mg, 1.2 mmol), nitrogen-containing heterocycle (0.5 mmol), aryl or heteroaryl halide (0.6 mmol) and H_2O (2 mL) under N_2. A rubber septum was replaced with a glass stopper, and the system was then evacuated three times and refilled with N_2. The reaction mixture was stirred for 30 min at room temperature, and then was irradiated for 10 min at 140 ℃. The resulting mixture was cooled to ambient temperature, diluted with ethyl acetate (2—3 mL), filtered through a plug of silica gel, and washed with ethyl acetate (10—20 mL). The filtrate was concentrated and the resulting residue was purified by column chromatography on silica gel to provide the desired product. Then, **5** was eluted with pole solvent (such as ethyl acetoacetate) for reuse in the next cycle of aqueous reaction directly.

1-*p*-Tolyl-1*H*-imidazole (**6a**): Yield 95%; white solid; m.p. 45—47 ℃ [Lit.[16] m.p. 45—46 ℃]; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.81 (s, 1H), 7.25—7.24 (bs, 4H), 7.19 (s, 1H), 7.17 (s, 1H), 2.39 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 137.4, 135.6, 134.9, 130.3 (2C) , 130.2, 121.4 (2C), 118.3, 21.2; MS (EI) *m/z*: 158 (M^+, 100), 130 (35).

1-Phenyl-1*H*-imidazole (**6b**): Yield 87%; yellow oil;[16] ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.84 (s, 1H), 7.50—7.42 (m, 2H), 7.41—7.32 (m, 3H), 7.29—7.24 (m, 1H), 7.19 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 137.1, 135.3, 130.2, 129.6 (2C), 127.2, 121.3 (2C), 118.0; MS (EI) *m/z*: 144 (M^+, 100), 117 (45).

4-(1*H*-Imidazol-1-yl)benzaldehyde (**6c**): Yield 85%; pale yellow solid; m.p. 144—145 ℃ [Lit.[17] m.p. 147—148 ℃]; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 10.03 (s, 1H), 8.10—7.90 (m, 3H), 7.57 (d, *J*=8.4 Hz, 2H), 7.37 (s, 1H), 7.26 (d, *J*=5.9 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 190.3, 141.5, 135.2, 134.7, 131.4 (2C), 131.1, 120.9 (2C), 117.5; MS (EI) *m/z*: 172 (M^+, 100), 171 (20).

4-(1*H*-Imidazol-1-yl)aniline (**6d**): Yield 85%; pale yellow solid; m.p. 141—143 ℃ [Lit.[18] m.p. 143—147 ℃]; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.70 (s, 1H), 7.14 (t, *J*=5.8 Hz, 4H), 6.72 (d, *J*=8.5 Hz, 2H), 3.82 (s, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 145.9, 135.6, 129.5, 128.5, 123.1 (2C), 118.7, 115.3 (2C); MS (EI) *m/z*: 159 (M^+, 100), 132 (20).

Ethyl 4-(1*H*-imidazol-1-yl)benzoate (**6e**): Yield 91%; pale white solid; m.p. 101—103 ℃ [Lit.[19] m.p. 101—103 ℃]; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.15 (d, *J*=8.4 Hz, 2H), 7.94 (s, 1H), 7.45 (d, *J*=8.4 Hz, 2H), 7.34 (s, 1H), 7.23 (s, 1H), 4.40 (q, *J*=7.1 Hz, 2H), 1.42 (t, *J*=7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 165.6, 140.7, 135.6, 131.7 (2C), 131.2, 129.5, 120.7 (2C), 118.0, 61.6, 14.8; MS (EI) *m/z*: 216 (M^+, 90), 171 (100).

1-(Naphthalen-1-yl)-1*H*-imidazole (**6f**): Yield 75%; white solid; m.p. 62—64 ℃ [Lit.[16] m.p. 61—63 ℃]; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.91 (d, *J*=7.9 Hz, 2H), 7.73 (s, 1H), 7.60—7.45 (m, 4H), 7.41 (dd, *J*=7.2, 1.0 Hz, 1H), 7.27 (d, *J*=6.9 Hz, 1H), 7.22 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 138.4, 134.1, 134.0, 129.6, 129.4, 129.2, 128.3, 127.6, 126.9, 125.2, 123.6, 122.3, 121.7; MS (EI) *m/z*: 194 (M^+, 100), 193 (32), 167 (34), 166 (37).

1-(Thiophen-2-yl)-1*H*-imidazole (**6g**): Yield 94%; yellow oil;[16] ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.74 (s, 1H), 7.21—7.09 (m, 3H), 7.03—6.92 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 138.8, 136.8, 130.0, 126.1, 121.6, 120.1, 118.8; MS (EI) *m/z*: 150 (M^+, 100), 96 (38).

1-(4-Nitrophenyl)-1*H*-imidazole (**6h**): Yield 98%; yellow solid; m.p. 204—206 ℃ [Lit.[20] m.p. 202—204 ℃]; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.37 (d, *J*=8.8 Hz, 2H), 7.99 (s, 1H), 7.59 (d, *J*=8.8 Hz, 2H), 7.38 (s, 1H), 7.27 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 146.0, 141.7, 135.2, 131.5, 125.6 (2C), 120.9 (2C), 117.5; MS (EI) *m/z*: 189 (M^+, 100).

5-Nitro-1-phenyl-1*H*-indole (**6i**): Yield 97%; yellow solid; m.p. 82—83 ℃ [Lit.[21] m.p. 83 ℃]; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.62 (d, *J*=2.1 Hz, 1H), 8.09 (dd, *J*=9.1, 2.2 Hz, 1H), 7.59—7.41 (m, 7H), 6.84 (d, *J*=3.2 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 142.2, 138.8, 138.7, 131.4, 130.1 (2C), 128.6, 127.9, 124.8 (2C), 118.4, 118.1, 110.7, 105.8; MS (EI) *m/z*: 238 (M^+, 100), 192 (45), 191 (71).

1-Phenyl-1*H*-benzo[*d*][1,2,3]triazole (**6j**): Yield 95%; white solid; m.p. 92—93 ℃ [Lit.[22] m.p. 85—87 ℃]; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.13 (d, *J*=8.3 Hz, 1H), 7.75 (dd, *J*=14.7, 8.3 Hz, 3H), 7.59 (t, *J*=7.6 Hz, 2H), 7.56—7.45 (m, 2H), 7.41 (t, *J*=7.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 145.9, 136.4, 131.7, 129.3, 128.1, 127.7, 123.9, 122.3, 119.8, 109.9; MS (EI) *m/z*: 195 (M^+, 20), 167 (100), 166 (50).

2-Methyl-1-phenyl-1*H*-indole (**6k**): Yield 77%; yellow oil;[21] ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.57—7.45 (m, 3H), 7.40 (t, *J*=7.1 Hz, 1H), 7.31 (d, *J*=7.7 Hz, 2H), 7.12—7.02 (m, 3H), 6.38 (s, 1H), 2.28 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 138.0, 137.8, 136.8, 129.2 (2C), 128.0, 127.8 (2C), 127.5, 120.9, 119.9, 119.4, 109.9, 101.2, 13.5; MS (EI) *m/z*: 207 (M^+, 100), 206 (75).

1-*p*-Tolyl-1*H*-indole (**6l**): Yield 90%; yellow oil;[21] ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.66 (d, *J*=7.7 Hz, 1H), 7.51 (d, *J*=8.1 Hz, 1H), 7.37 (d, *J*=8.2 Hz, 2H), 7.32—7.27 (m, 3H), 7.16 (dt, *J*=14.7, 7.1 Hz, 2H), 6.65 (d, *J*=3.2 Hz, 1H), 2.43 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 137.4, 136.3, 136.1, 130.3 (2C), 129.3, 128.2, 124.5 (2C), 122.4, 121.2, 120.3, 110.7, 103.4, 21.46; MS (EI) *m/z*: 207 (M^+, 100), 206 (36).

1-*p*-Tolyl-1*H*-1,2,4-triazole (**6m**): Yield 96%; white

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solid; m.p. 66—67 ℃ [Lit.[23] m.p. 67—67.5 ℃]; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.50 (s, 1H), 8.07 (s, 1H), 7.53 (d, J=8.2 Hz, 2H), 7.28 (d, J=8.1 Hz, 2H), 2.40 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 152.1, 140.5, 138.0, 134.5, 130.0 (2C), 119.8 (2C), 21.1; MS (EI) *m/z*: 159 (M^+, 100), 105 (70).

1-Phenyl-1*H*-pyrazole (**6n**): Yield 92%; colorless oil;[21] ^{1}H NMR (400 MHz, CDCl3) δ: 7.91—7.90 (m, 1H), 7.71—7.67 (m, 3H), 7.43 (t, J=7.8 Hz, 2H), 7.28—7.24 (m, 1H), 6.45 (t, J=1.6 Hz, 1H); ^{13}C NMR (100 MHz, CDCl3) δ: 140.9, 140.0, 129.3 (2C), 126.6, 126.3, 119.1 (2C), 107.5; MS (EI) *m/z*: 144 (M^+, 100).

3,4-Dimethyl-1-phenyl-1*H*-pyrazole (**6o**): Yield 73%; colorless oil;[24] ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.99—7.89 (m, 2H), 7.72—7.64 (m, 3H), 7.61 (s, 1H), 2.10 (s, 3H), 2.00 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 149.1, 139.9, 132.5, 129.7 (2C), 128.0, 119.9 (2C), 119.4, 12.2, 7.2; MS (EI) *m/z*: 172 (M^+, 50), 171 (100).

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