
pH-Responsive N-heterocyclic carbene copper (I) complexes: syntheses and recoverable applications in the carboxylation of arylboronic esters and benzoxazole with carbon dioxide

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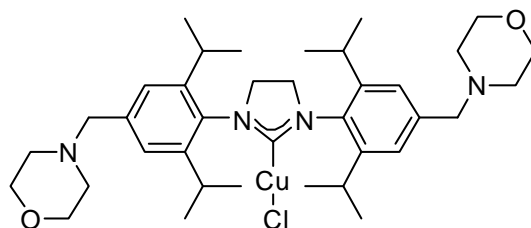
1. General Remarks

All the chemical and solvents were used as received without purification except THF and ether, which was dried by distillation over sodium and freshly distilled prior to use. Unless otherwise noted, all reactions were performed under argon atmosphere using standard Schlenk-line techniques. 1,3-bis(2,6-diisopropyl-4-(morpholinomethyl)phenyl)-4,5-dihydro-1H-imidazol-3-ium chloride (**5**) was synthesized according to the reported procedure¹. NMR spectra were recorded using a Bruker Avance TM III spectrometer operating at 400 MHz for ¹H and 100 MHz for ¹³C. Chemical shifts are given in ppm relative to TMS or to residual solvent proton resonances. High resolution mass spectra (HRMS) were obtained on a Bruker micrOTOF-QII spectrometer. All the reported yields in the catalytic studies are isolated yields and averaged by at least two runs.

2. Preparation of morpholine functionalized Cu(I)-NHC and Ag(I)-NHC complexes

(1,3-bis(2,6-diisopropyl-4-(morpholinomethyl)phenyl)imidazolidin-2-ylidene)copper(I)chloride (**6a**)

An oven-dried Schlenk flask was charged with **5** (625 mg, 1.0 mmol), CuCl (109 mg, 1.1 mmol) and KO^t-Bu (135 mg, 1.0 mmol). The flask was evacuated and backfilled with argon three times before the addition of dried THF (30 mL), then the mixture was stirring at room temperature for 24 hours. After the completion of reaction, the resultant reaction mixture was filtered through a plug of celite, and the filtrate was concentrated to about 10 mL under reduced pressure. Upon the addition of pentane to the crude reaction mixture, complex **6a** was slowly precipitated and isolated as a white powder (592 mg, 86%).

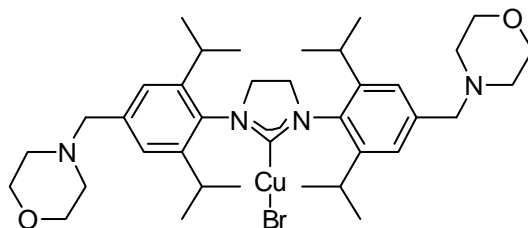


¹H NMR (CDCl₃): 1.35 (t, 24 H, *J* = 6.6 Hz), 2.49 (s, 8 H), 3.00-3.07 (m, 4 H), 3.53 (s, 4 H), 3.75 (s, 8 H), 4.01 (s, 4 H), 7.20 (s, 4 H). ¹³C NMR (CDCl₃): 24.0, 25.5, 29.1, 53.8, 63.3, 67.1, 125.1, 133.4, 139.4, 146.6, 203.2. HRMS *m/z* (ESI) calcd for C₃₇H₅₆ClCuN₄O₂ [M+H]⁺ 687.3461, found 687.3427.

(1,3-bis(2,6-diisopropyl-4-(morpholinomethyl)phenyl)imidazolidin-2-ylidene)copper(I)bromide (**6b**)

An oven-dried Schlenk flask was charged with **5** (625 mg, 1.0 mmol), CuBr·SMe₂ (226 mg, 1.1 mmol) and KO^t-Bu (135 mg, 1.0 mmol). The flask was evacuated and backfilled with argon three times before the addition of dried THF (30 mL), then the mixture was stirring at room temperature for 24 hours. After the completion of reaction, the resultant reaction mixture was filtered through a plug of celite, and the filtrate was concentrated to about 10 mL under reduced pressure. Upon the addition of pentane to the crude reaction mixture, complex **6b** was slowly precipitated and isolated

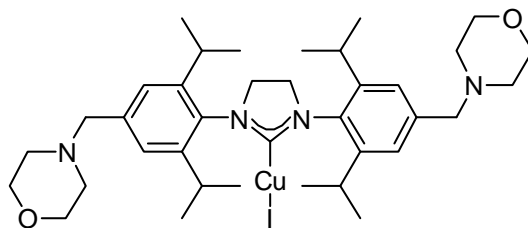
as a white powder (593 mg, 81%).



^1H NMR (CDCl_3): 1.34 (dd, 24 H, $J = 4.8, 6.8$ Hz), 2.90 (s, 4 H), 2.98-3.08 (m, 4 H), 3.88 (t, 8 H, $J = 4.6$ Hz), 3.92 (s, 4 H), 4.04 (s, 4 H), 7.26 (s, 4 H). ^{13}C NMR (CDCl_3): 24.1, 25.5, 29.1, 52.4, 53.8, 62.0, 65.2, 126.9, 134.9, 147.5, 203.7. HRMS m/z (ESI) calcd for $\text{C}_{37}\text{H}_{56}\text{BrCuN}_4\text{O}_2$ $[\text{M}+\text{H}]^+$ 731.2955, found 731.2931.

(1,3-bis(2,6-diisopropyl-4-(morpholinomethyl)phenyl)imidazolidin-2-ylidene)copper(I)iodide (6c)

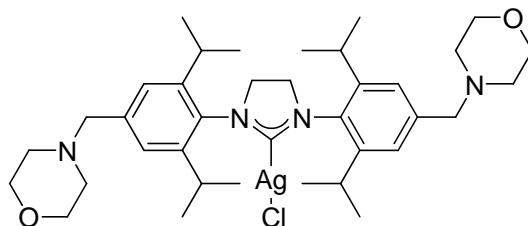
An oven-dried Schlenk flask was charged with **5** (625 mg, 1.0 mmol), CuI (209 mg, 1.1 mmol) and KO t -Bu (135 mg, 1.0 mmol). The flask was evacuated and backfilled with argon three times before the addition of dried THF (30 mL), then the mixture was stirring at room temperature for 24 hours. After the completion of reaction, the resultant reaction mixture was filtered through a plug of celite, and the filtrate was concentrated to about 10 mL under reduced pressure. Upon the addition of pentane to the crude reaction mixture, complex **6c** was slowly precipitated and isolated as a white powder (654 mg, 84%).



^1H NMR (CDCl_3): 1.35 (dd, 24 H, $J = 6.8, 9.4$ Hz), 2.48 (s, 8 H), 2.99-3.09 (m, 4 H), 3.53 (s, 4 H), 3.74 (t, 8 H, $J = 4.4$ Hz), 4.02 (s, 4 H), 7.20 (s, 4 H). ^{13}C NMR (CDCl_3): 24.2, 25.7, 29.1, 53.8, 63.4, 67.2, 125.2, 133.2, 146.6. HRMS m/z (ESI) calcd for $\text{C}_{37}\text{H}_{56}\text{ICuN}_4\text{O}_2$ $[\text{M}+\text{H}]^+$ 779.2817, found 779.2772.

(1,3-bis(2,6-diisopropyl-4-(morpholinomethyl)phenyl)imidazolidin-2-yl)silver(I) chloride (9)

An oven-dried Schlenk flask was charged with **5** (625 mg, 1.0 mmol), Ag $_2$ O (139 mg, 0.65 mmol), The flask was evacuated and backfilled with argon three times before the addition of dried CH_2Cl_2 (5 mL), then the mixture was refluxing for 24 hours. After the completion of reaction, the resultant reaction mixture was filtered through a plug of celite. Upon the addition of pentane to the crude reaction mixture, complex **9** was slowly precipitated and isolated as a white powder (638 mg, 87%).



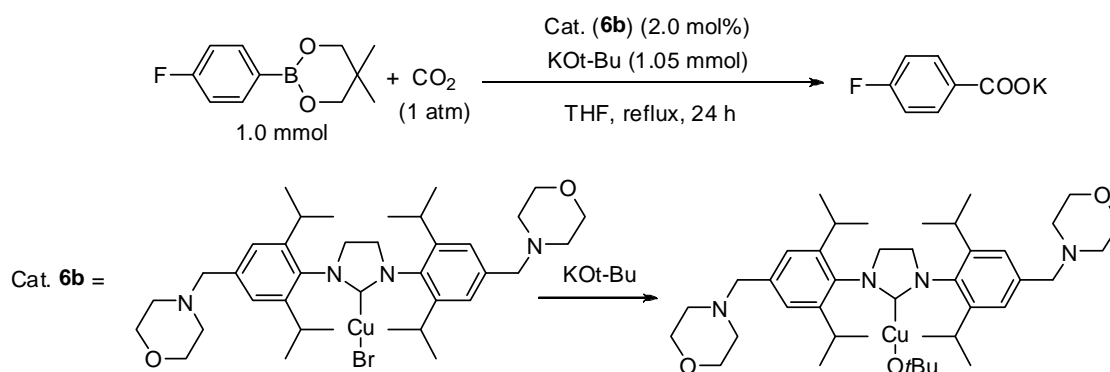
^1H NMR (CDCl_3): 1.338(d, 24 H, $J = 6.8$ Hz), 2.496 (s, 8 H), 2.975-3.077 (m, 4 H), 3.525 (s, 4 H), 3.757 (s, 8 H), 4.049 (s, 4 H), 7.198 (s, 8 H). ^{13}C NMR (CDCl_3): 24.2, 25.5, 29.0, 54.0, 63.3, 67.2, 125.2, 133.5, 139.9, 146.5 HRMS m/z (ESI) calcd for $\text{C}_{37}\text{H}_{56}\text{AgClN}_4\text{O}_2$ $[\text{M}+\text{H}]^+$ 823.2572, found 823.2579.

3. Synthesis of organoboronic esters

General procedure for the synthesis of arylboronic acid ester from arylboronic acid with 2,2-Dimethyl-1,3-propanediol (5 mmol scale).

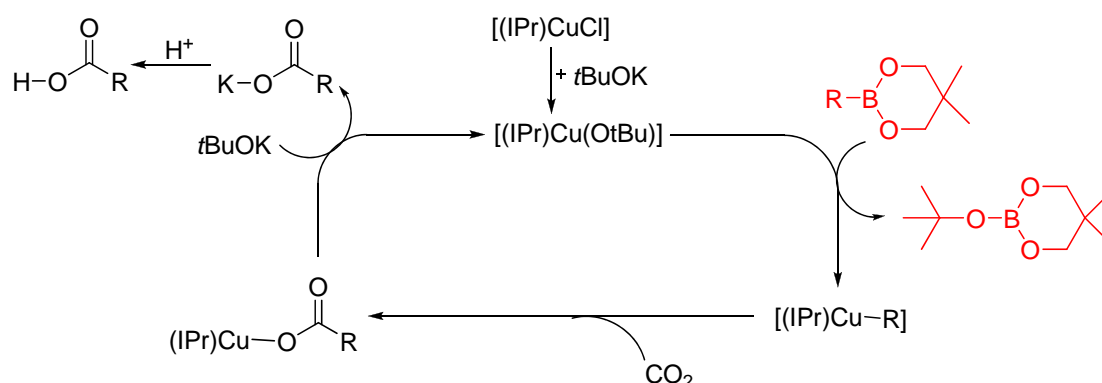
In a 50 mL flask equipped with a stir-bar, arylboronic acid (5 mmol) and 2,2-dimethyl-1,3-propanediol (6 mmol) were combined. 15 mL ether was added to the flask and the solution was stirred for 6 hours under room temperature. The ether was then removed under vacuum to get the white solid mixture. The mixture was then washed three times with water to remove the excess 2,2-dimethyl-1,3-propanediol. The product was dried at 50°C under vacuum.

4. Detailed experimental procedures for catalyst recycling



Step I:

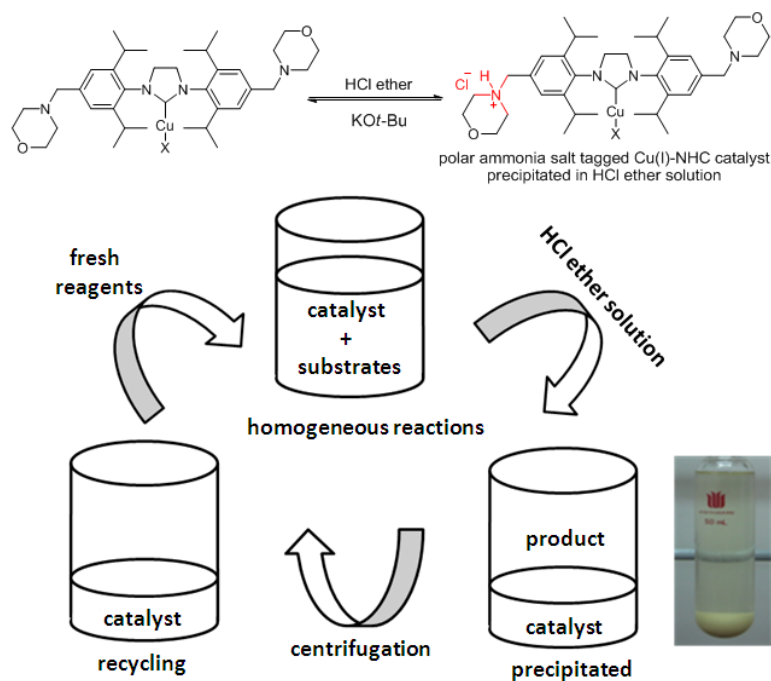
Scheme 1 NHC-Cu(I)-catalyzed carboxylation of organoboronic esters.



Scheme 2 A possible mechanism for (IPr)Cu-catalyzed carboxylation of organoboronic esters with CO₂.

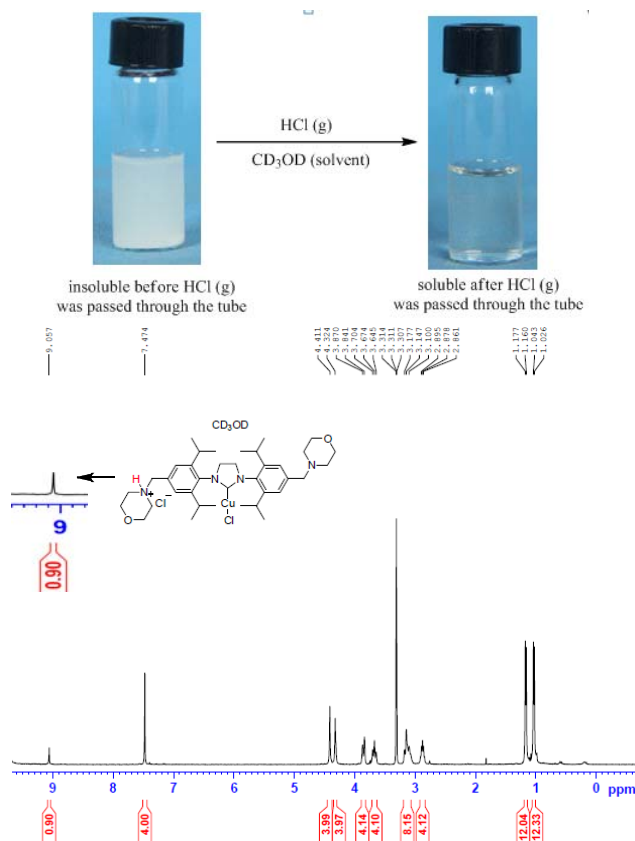
A 50 mL Schlenk tube was equipped with arylboronic acid ester (208 mg, 1.0 mmol), catalyst **6b** (15 mg, 2.0 mol%), KO*t*-Bu (117 mg, 1.05 mmol). The tube was evacuated and backfilled with argon three times before the addition of dried THF (5 mL), then CO₂ (1 atm) was introduced through Schlenk-line. The mixture was refluxed for 24 hours, after the completion of the reaction, the resultant RCOOK precipitated from the THF solution.

Step II:



The finished reaction tube in Step I was added with 40 mL HCl diethylether solution, then the mixture was stirring at r.t. for 5 minutes.

^1H NMR evidence :



Step III:



centrifugation

Liquid phase : RCOOH in HCl diethylether solution

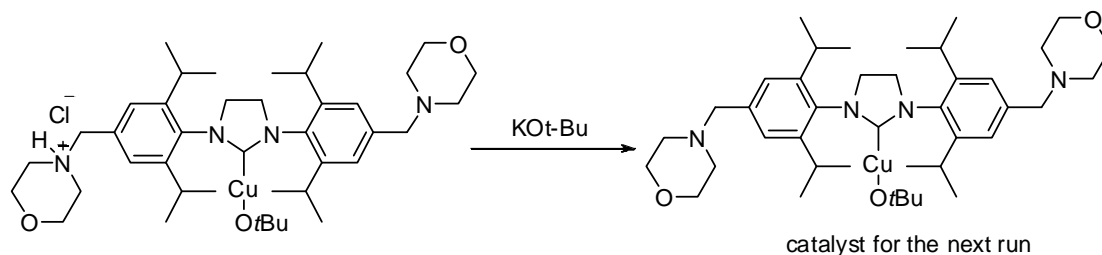
↓
distillation in reduced pressure

↓
chromatography

Solid phase: ammonia salt tagged
Cu(I)-NHC-catalyst

The RCOOH in HCl diethylether solution and solid ammonium salt tagged Cu(I)-NHC catalyst in the acidified reaction mixture in Step II was isolated through centrifugation, then the liquid phase was distilled in reduced pressure, following with silica gel chromatography to obtain the pure product.

Step IV:



The solid phase was dried under vacuum at 50°C for 12 h, and then was used for the next run. The polar ammonia salt tagged Cu(I)-NHC catalyst was transferred to its primary form automatically by the existence of excess $\text{KO}t\text{-Bu}$.

5. Detailed experimental procedures of Cu(I)-NHC-catalyzed carboxylation of aromatic heterocycles with CO_2 .

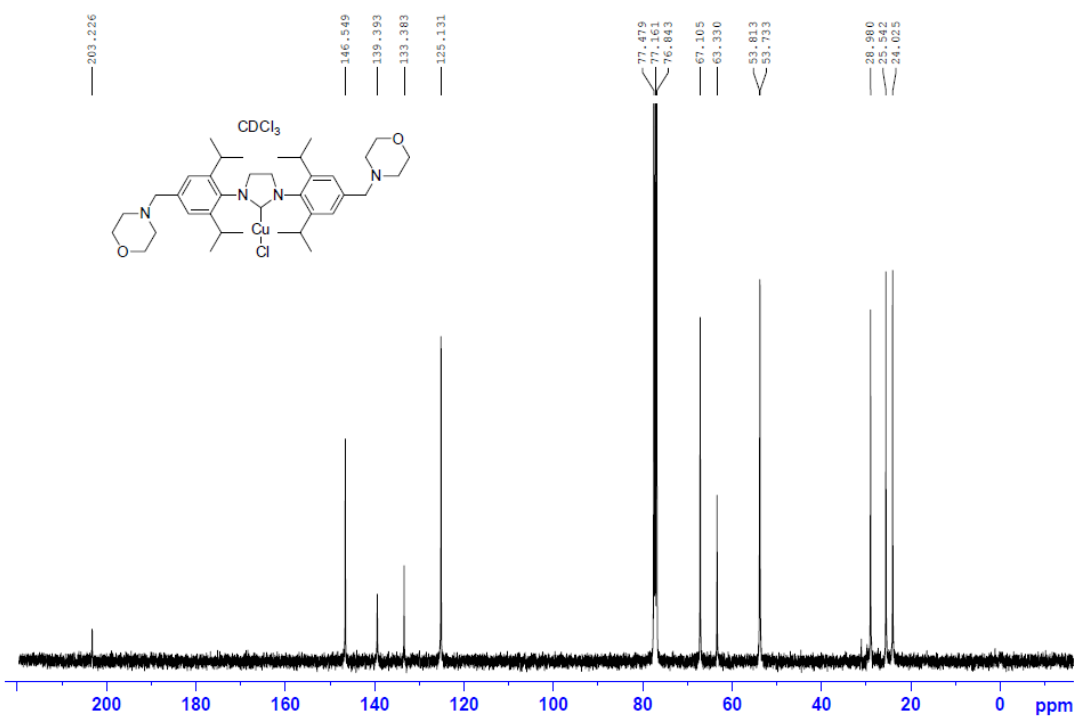
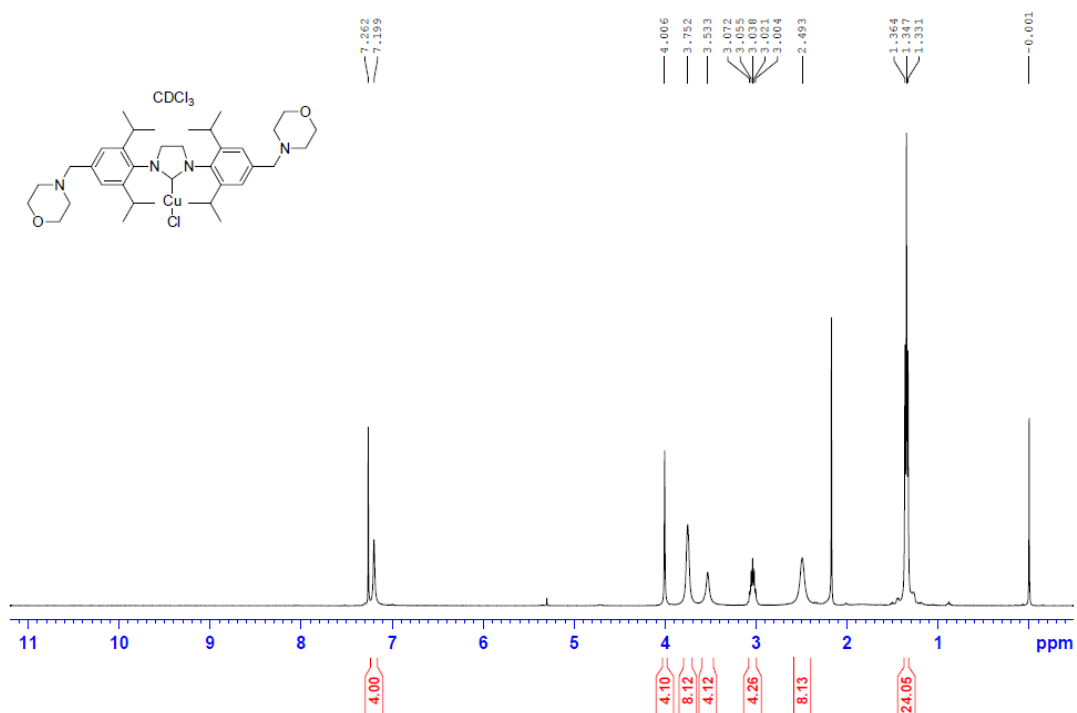
A 50 mL Schlenk tube was charged with $\text{KO}t\text{-Bu}$ (123 mg, 1.1 mmol), catalyst **6a** (34 mg, 5 mol%) and THF (3 mL) under nitrogen atmosphere. The reaction mixture was subjected to vacuum for a while, CO_2 (1 atm) was introduced to the reaction tube. Then heterocycle substrate (1.0 mmol) in THF (2 mL) was added into the reaction tube. The Schlenk tube was stirred at 80°C for 8 h. After the reaction mixture was cooled to room temperature, the solvent was removed under reduced pressure. DMF (2 mL) and Methyl iodide (0.13 mL, 2.0 mmol) were added to the residue solid under a nitrogen flow. The sealed Schlenk tube was stirred again at 80°C for 1 h. After the reaction mixture was cooled to room temperature, 50 mL HCl diethylether was added to the mixture, then the mixture was stirring at r.t. for 5 minutes. The RCOOH in HCl diethylether solution and solid ammonium salt tagged Cu(I)-NHC catalyst in the acidified reaction mixture was isolated through centrifugation, then the liquid phase was distilled in reduced pressure, following with silica gel chromatography to obtain the pure product.

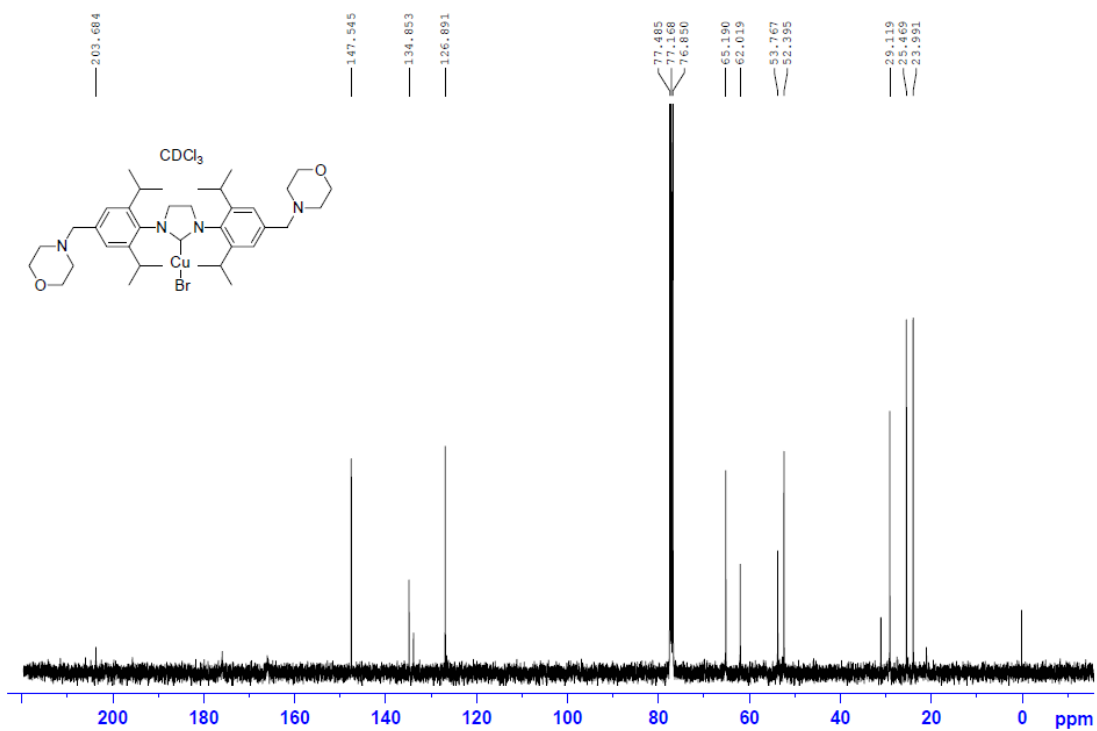
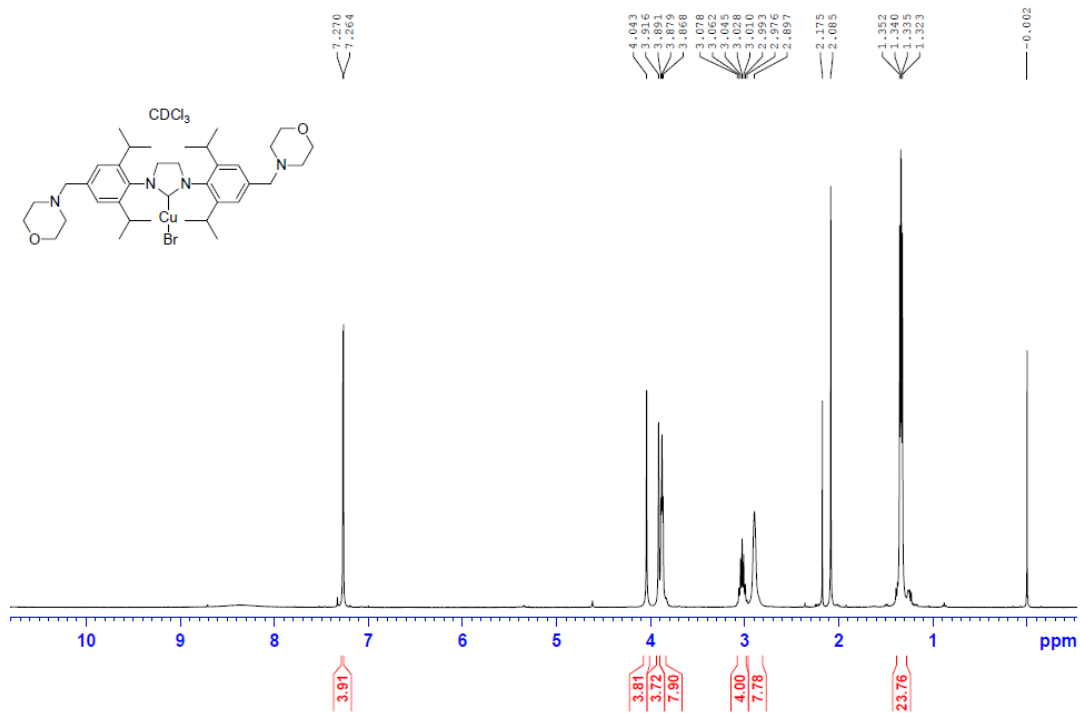
6. Detailed experimental procedures of Ag(I)-NHC-catalyzed carboxylation of terminal alkynes with CO_2

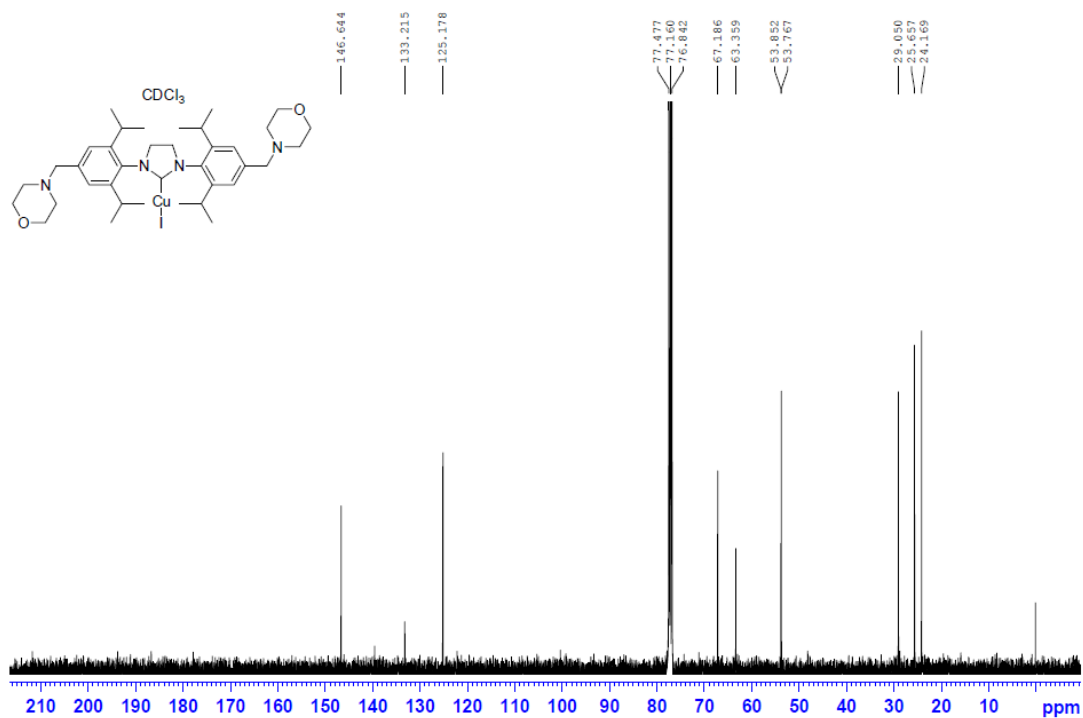
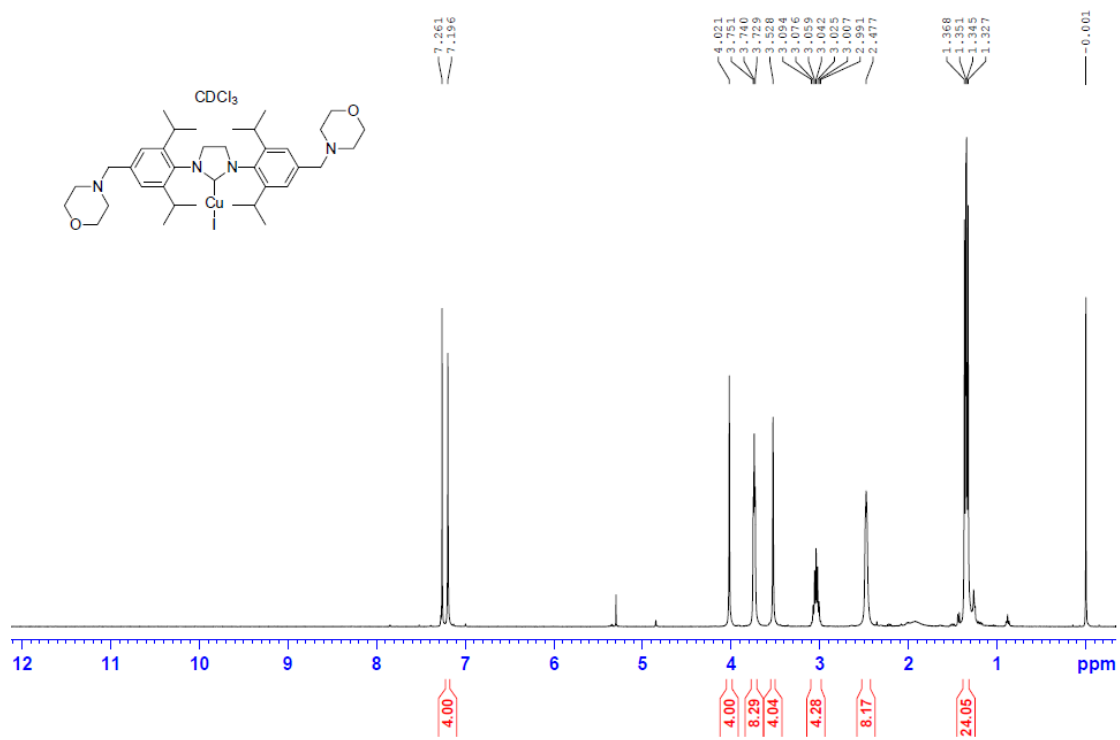
A 50 mL Schlenk tube was charged with Cs_2CO_3 (391 mg, 1.2 mmol), catalyst **9** (73 mg, 10 mol%) and alkyne (1.0 mmol) and DMF (2 mL) under CO_2 atmosphere. The sealed tube was pressurized to 0.2 MPa with CO_2 . The reaction mixture was stirred at 60°C for 12 h, then was cooled to room temperature and the remaining CO_2 was vented slowly. 50 mL HCl diethylether was added to the mixture, then the mixture was stirring at r.t. for 5 minutes. The RCOOH in HCl diethylether solution and solid ammonium salt tagged Cu(I)-NHC catalyst in the acidified reaction mixture was isolated through centrifugation, then the liquid phase was distilled in reduced pressure, following with silica gel chromatography to obtain the pure product.

7. ^1H NMR and ^{13}C NMR copies

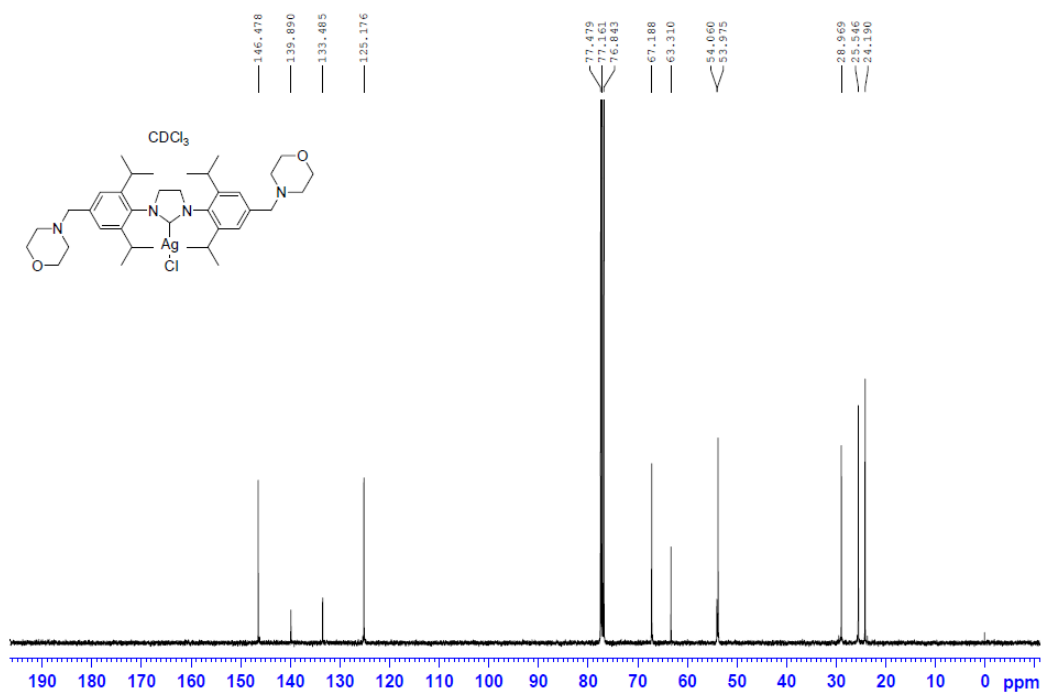
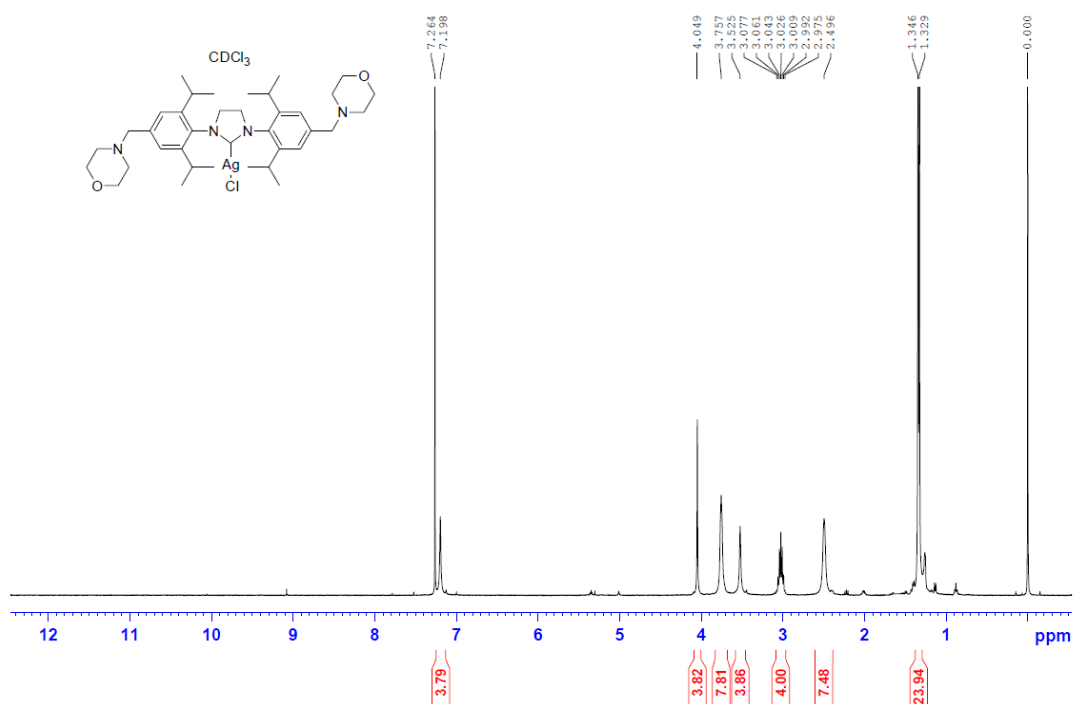
7.1. NMR copies for new compound



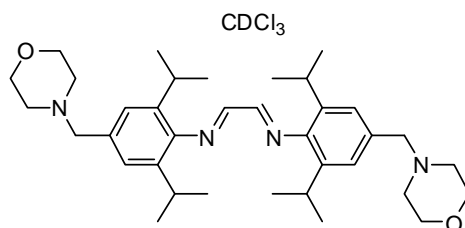




100928-1-WANGWL-HNMR (6)



7.2 ^1H NMR copies for known compounds



100809-4-WangWL-HNMR (27)

