# Carboxylation of Terminal Alkynes with Carbon Dioxide Catalyzed by Poly(N–Heterocyclic Carbene)–Supported Silver Nanoparticles

3 **AUTHORS**, INCLUDING:

Yugen Zhang

Agency for Science, Technology and Resear…

**122** PUBLICATIONS **3,648** CITATIONS

# Carboxylation of Terminal Alkynes with Carbon Dioxide Catalyzed by Poly(N-Heterocyclic Carbene)-Supported Silver Nanoparticles

Dingyi Yu,[a] Mei Xuan Tan,[a] and Yugen Zhang[a,*]

[a] Institute of Bioengineering and Nanotechnology, 31 Biopolis Way, The Nanos, Singapore 138669, Singapore
Fax: (+65)-6-498-9080; phone: (+65)-6-824-7162; e-mail: ygzhang@ibn.a-star.edu.sg

Supporting information for this article is available on the WWW under
http://dx.doi.org/10.1002/adsc.201100934.

**Abstract:** An N-heterocyclic carbene (NHC) polymer supported silver nanoparticle catalyst system was developed. The novel nano-composite catalyst demonstrated very high activity and excellent stability and reusability in the carboxylation of terminal alkynes with carbon dioxide at ambient conditions. The unique N-heterocyclic carbene polymer and silver nanoparticle composite structure provided a synergistic effect on activation of terminal alkynes and carbon dioxide that contributed to the high catalytic activity. The poly-NHC-silver catalyst exhibited excellent substrate generality and tolerance to various functionalities. In addition, the catalyst is stable to air and moisture and can be easily recovered and reused.

**Keywords:** carbon dioxide; carboxylation; N-heterocyclic carbenes; silver catalyst; terminal alkynes

The use of $CO_2$ as a $C_1$ building block in organic synthesis has attracted increasing attention since it may provide access to high-value products from a non-toxic, renewable, and low-cost resource.[1–16] Among these procedures, the direct carboxylation of carbon nucleophiles using $CO_2$ as the electrophile with C–C bond formation represents one of the most attractive and straightforward protocols. Recently, the carboxylation of terminal alkynes with $CO_2$ to produce propiolic acids has been developed by several groups.[17–20] The ubiquity of alkynyl carboxylic acids is demonstrated by their tremendous utility as a synthon in organic synthesis as well as being one of the most important types of compounds in medicinal chemistry.[21–24] Furthermore, the propiolic acids can also be used for the preparation of alkynylarenes or aminoalkynes *via* decarboxylative cross-coupling reactions.[25–27] There are some well-established protocols for the preparation of alkynyl carboxylic acids, such as the hydrolysis of bromide and relative derivatives and the oxidation of alcohols or aldehydes.[28–30] However, the catalytic carboxylation of terminal alkynes with $CO_2$ is the most straightforward method for the synthesis of alkynyl carboxylic acids. Typically, this type of reaction is facilitated by the insertion of $CO_2$ into a carbon-metal bond. We and Gooben's group have recently disclosed a copper- or copper-NHC-catalyzed carboxylation of terminal alkynes with $CO_2$ (Scheme 1, A and B).[17,19] Later, we have developed a transition metal-free method for direct carboxylation of terminal alkynes with $CO_2$ under heating condition and 2.5 atm (Scheme 1, C).[18] Following that, a ligand-free Ag(I) catalytic system was reported to catalyze the carboxylation of terminal alkynes with $CO_2$ under mild conditions (50–60°C, 2 atm) (Scheme 1, D).[20] In addition, copper-catalyzed coupling $CO_2$ with terminal alkynes and alkyl halides to form propiolic acid esters was also reported.[31–33] These elegant methods certainly represented a milestone for propiolic acids synthesis. However, there are still some limitations of these catalytic systems for carboxylation of terminal alkynes with $CO_2$, such as moderate to good yield, heating and pressure conditions and no catalyst reusability was reported.

Herein, we report a poly-NHC supported silver nanoparticle (poly-NHC-Ag) system that can serve as an excellent and reusable heterogeneous catalyst for the carboxylation of terminal alkynes with $CO_2$ (Scheme 1, E). The reaction can be carried out in the presence of poly-NHC-Ag nanocomposite under ambient conditions to afford excellent yields of propiolic acids with a wide range of functionality.

Previously, we have reported a poly-N-heterocyclic carbene (NHC) and copper(I) catalytic system for the carboxylation of terminal alkynes with $CO_2$.[17] The synergistic effects of the organocatalyst (NHC) and
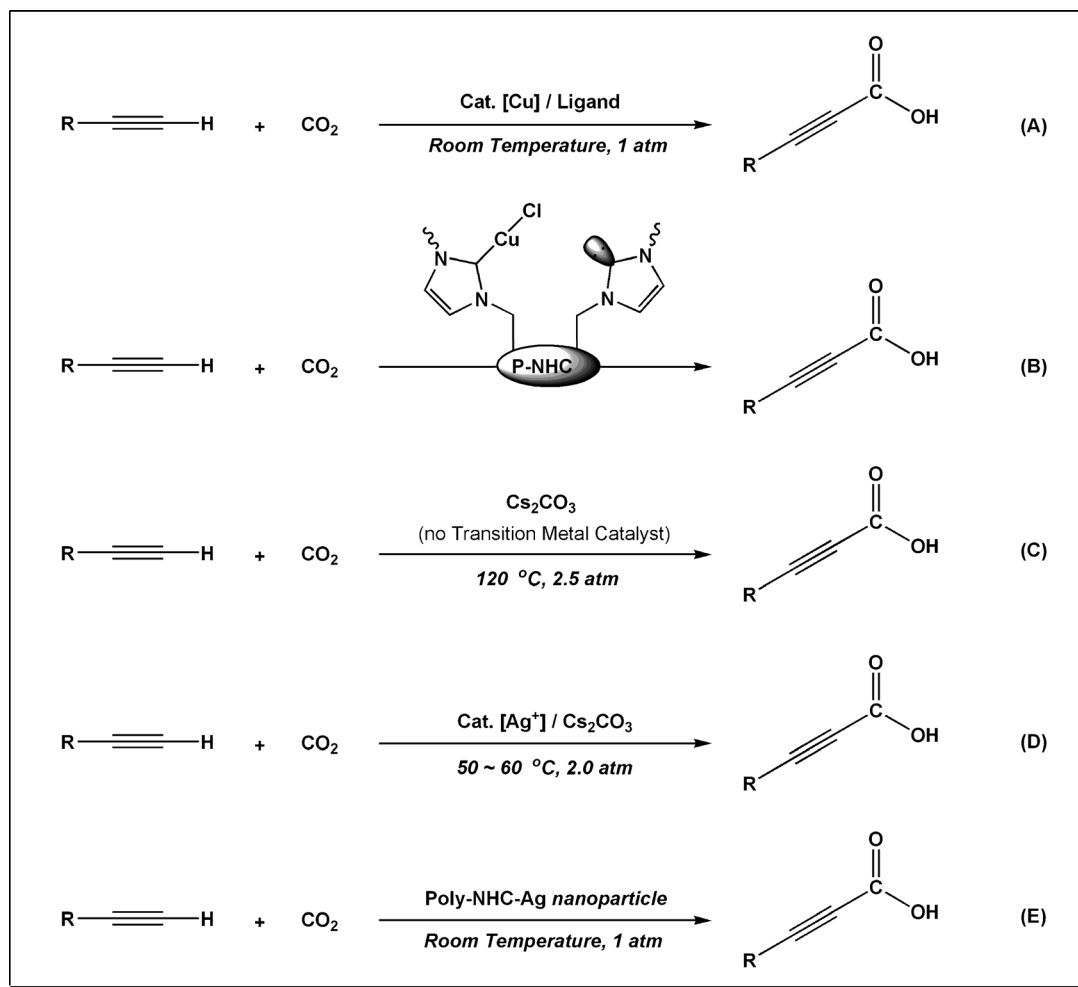
**Scheme 1.** Protocols for synthesis of substituted propiolic acids from terminal alkynes and $CO_2$.

organometallic catalyst make the composite catalyst much more active, especially for arylalkynes with electron-withdrawing groups which are typically inner toward copper catalysts. Later, Lu's group reported a simple AgI catalyst that is active toward aryalkynes with either electron-withdrawing groups or electron-donating groups under relatively mild conditions (50°C, 2 atm) even with very low catalyst loading.[20] With the intention to develop a high efficient catalyst that is active toward a general and wide range of alkyne substrates and yet stable and reusable, a poly-NHC/Ag nanoparticle composite catalyst was designed and synthesized. The synergistic effect of NHC and Ag nanoparticles was proposed to play a major role in the catalytic cycle.

The poly-imidazolium material was synthesized based on the literature method.[34–36] The poly-NHC-supported silver nanoparticle (poly-NHC-Ag) material was prepared by reacting the poly-imidazolium with $AgNO_3$ in hot dimethyl sulfoxide (DMSO).[34] Transmission electron microscopy (TEM) image shows that silver nanoparticles (3–5 nm) were dispersed in poly-NHC polymer material (Figure 1). The conversion of poly-imidazolium into poly-N-heterocyclic carbene was confirmed by Fourier transform infrared and solid state NMR spectroscopy (see the Supporting Information, Figure S1).[34] The silver content in this poly-NHC-Ag nano-composite is 6.8 wt%. With that, the catalytic activity of poly-NHC-Ag nanocomposite was evaluated in the carboxylation reaction of 1-ethynylbenzene (**1a**) with $CO_2$ under ambient conditions (Table 1). Initial screening experiments gave very promising results. Up to 98% yield of the desired propiolic acid product was obtained with 0.3 mol% of poly-NHC-Ag catalyst under ambient condition in 20 h (Table 1, entry 4). Under the same reaction conditions, silver on carbon (Ag/C) and AgI (5 mol%) only gave 40% and 54% of the desired product. AgI (5 mol%) with N-heterocyclic carbene ligand (Imes) (10 mol%) gave 70% product yield (Table 1).

Inspired by this high catalytic activity, the stability and the reusability of poly-NHC-Ag nano-composite catalyst was further studied. The poly-NHC-Ag cata-
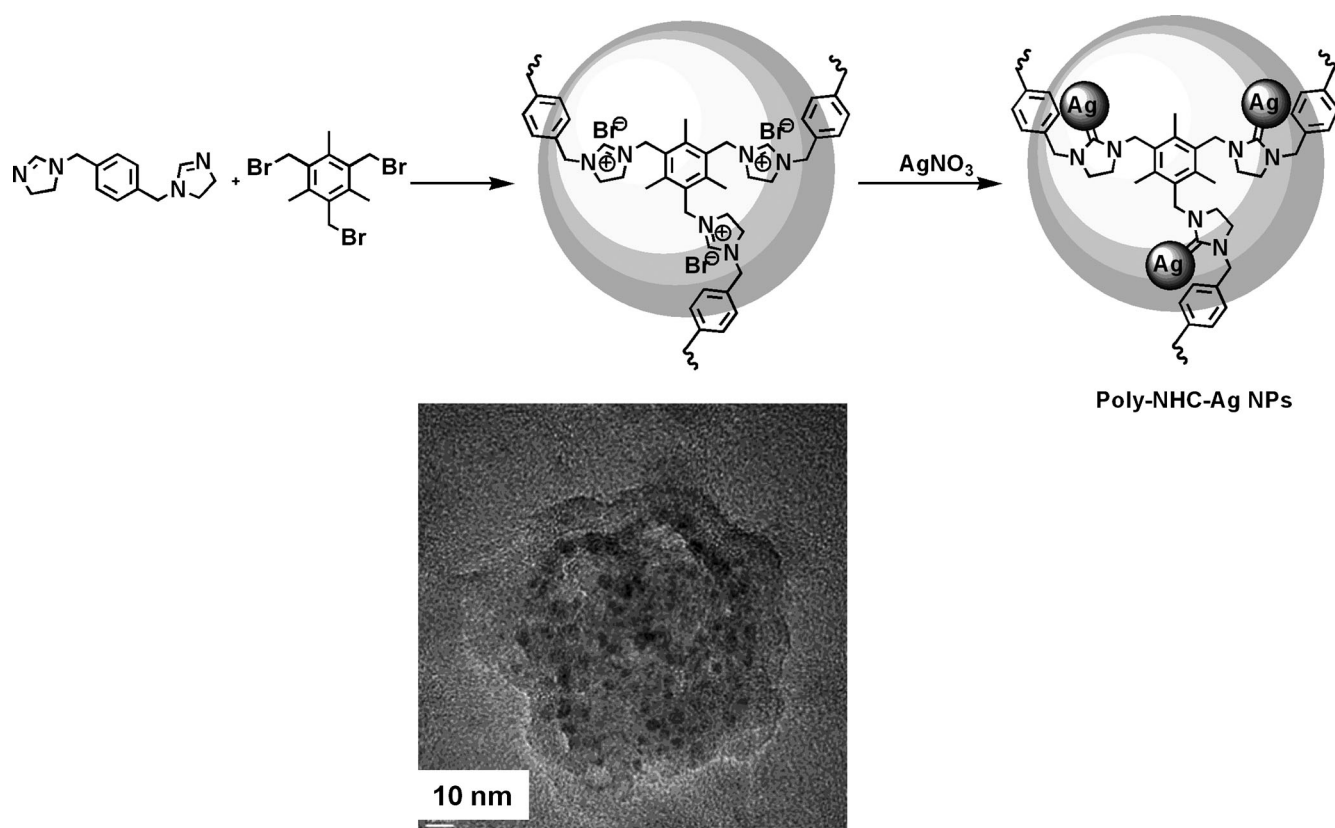
**Poly-NHC-Ag NPs**



**Figure 1.** Preparation of poly-NHC-Ag nano-composite and the transmission electron microscopy (TEM) image of the nano-composite.

**Table 1.** Carboxylation of 1-ethynylbenzene with $CO_2$.[a]
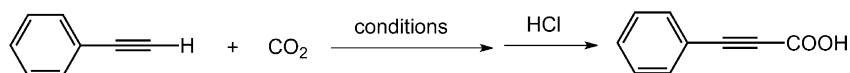


| Entry | Catalyst (mol% Ag) | Temperature [°C] | $CO_2$ [atm] | Time [h] | Yield [%][b] |
|---|---|---|---|---|---|
| 1 | Ag@C (5.0) | 25 | 1.0 | 20 | 40 |
| 2 | Ag@C (5.0) | 25 | 1.0 | 36 | 48 |
| 3 | Ag@C (5.0) | 50 | 2.0 | 20 | 68 |
| 4 | Ag@P-NHC (0.3) | 25 | 1.0 | 20 | 98 |
| 5 | AgI-IMes (5.0) | 25 | 1.0 | 20 | 70 |
| 6 | AgI (5.0) | 25 | 1.0 | 20 | 54 |

[a] *Reaction conditions:* 1-ethynylbenzene (1.0 mmol), $Cs_2CO_3$ (1.2 mmol), DMF (5 mL).
[b] GC yields.

lyst was recycled by centrifugation and filtration of the reaction mixture. The solid residue was washed with DMF twice and then directly used as the recycled catalyst in the subsequent runs. As shown in Figure 2, the catalytic activity of the poly-NHC-Ag nano-composite was maintained in a high level (more than 93% of yield in each of the 5 runs) although a slight decrease in activity was observed upon recycling. This decreasing activity may due to the partial loss of catalyst during the recovery process. In our heterogeneous reaction systems, no catalytic activity was observed in the hot filtrate solution. The Ag concentration in the filtrate was about 2.5 ppb as monitored by inductively coupled plasma-mass spectrometry (ICP-MS), which suggested that silver leakage (0.0037%) is negligible. In general, the poly-NHC-Ag catalyst exhibited excellent stability and reusability as a heterogeneous catalyst for the carboxylation terminal alkynes with $CO_2$. The total TON number for this catalyst in the first five runs was 1583 and this number could be further increased.
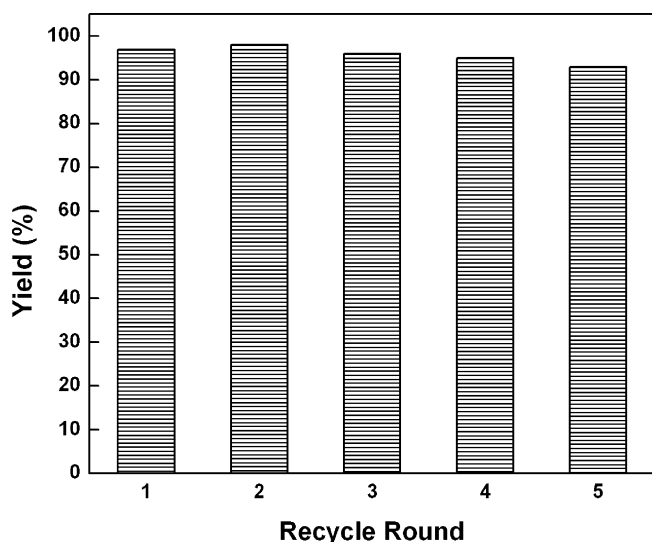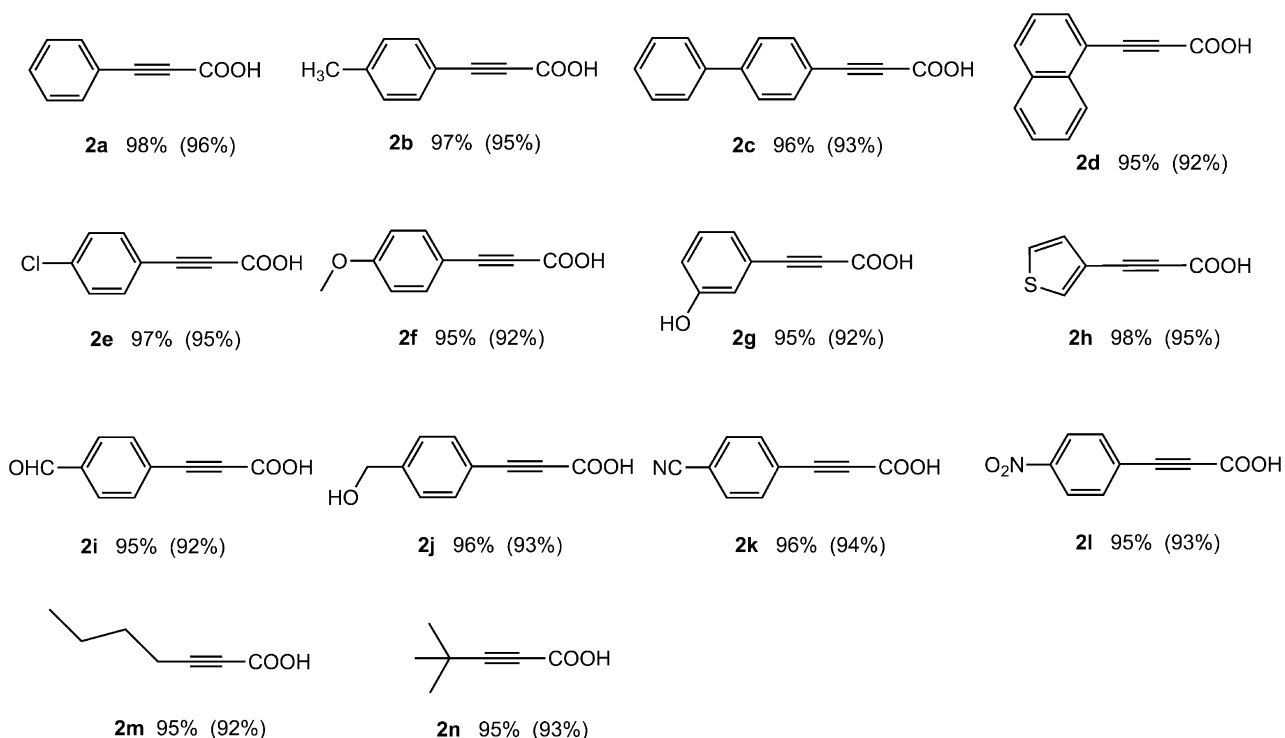
**Figure 2.** Recycling of poly-NHC-Ag nano-composite catalyst for the carboxylation of terminal alkynes with $CO_2$

To investigate the substrate scope and generality of the poly-NHC-Ag catalyst in this carboxylation reaction, a variety of different types of terminal alkynes were examined under the standard conditions: poly-NHC-Ag (5.0 mg, 0.3 mol% of Ag), 1.2 equivalents of $Cs_2CO_3$, 25°C and 1.0 atm) of $CO_2$ (see Scheme 2). As expected, the current catalyst is not sensitive to the functionality of the aromatic alkynes. Excellent yields (92–96%) were achieved for both arylalkynes with electron-donating groups (Scheme 2, **2b–2g**) and also with electron-withdrawing groups (Scheme 2, **2i–2l**). Excellent yields (95%) were also achieved for less active alkyl alkynes (Scheme 2, **2m** and **2n**). For both alkyl- and aryl-substituted alkynes,[37,38] the carboxylation reaction proceeded smoothly without any side product formation. It should also be noted that the poly-NHC-Ag nano-composite catalytic system is tolerant to various functional groups, such as OH, CHO, CN, $NO_2$ etc.

In general, copper(I)- and silver(I)-catalyzed carboxylation reactions of terminal alkynes with $CO_2$ follow a similar mechanism as that reported in the literature.[17,19,20] Silver or copper cations activate the terminal alkyne with base to form a metal acetylide intermediate, and then $CO_2$ inserts into the metal-carbon bond to form the carboxylic acid product. However, the current poly-NHC-Ag catalyst demonstrated extraordinary high activity as compared to other silver or copper catalysts. It is believed that the synergistic effect of the organocatalyst (NHC) and the organometallic catalyst (silver nanoparticle) plays the role here. In the poly-NHC-Ag catalytic system, silver nanoparticles activated the terminal alkyne with base to form a silver acetylide intermediate; meanwhile the free carbene of poly-NHC activated $CO_2$ to



**2a** 98% (96%)   **2b** 97% (95%)   **2c** 96% (93%)   **2d** 95% (92%)

**2e** 97% (95%)   **2f** 95% (92%)   **2g** 95% (92%)   **2h** 98% (95%)

**2i** 95% (92%)   **2j** 96% (93%)   **2k** 96% (94%)   **2l** 95% (93%)

**2m** 95% (92%)   **2n** 95% (93%)

**Scheme 2.** Carboxylation of terminal alkynes with $CO_2$. Unless otherwise noted, reaction conditions are as follows: alkyne (1.0 mmol), P-NHC-Ag catalyst (5.0 mg, 0.3 mol% of Ag), $Cs_2CO_3$ (1.2 mmol), $CO_2$ (1.0 atm), room temperature, DMF (5 mL). GC yields (isolated yields are in parentheses).
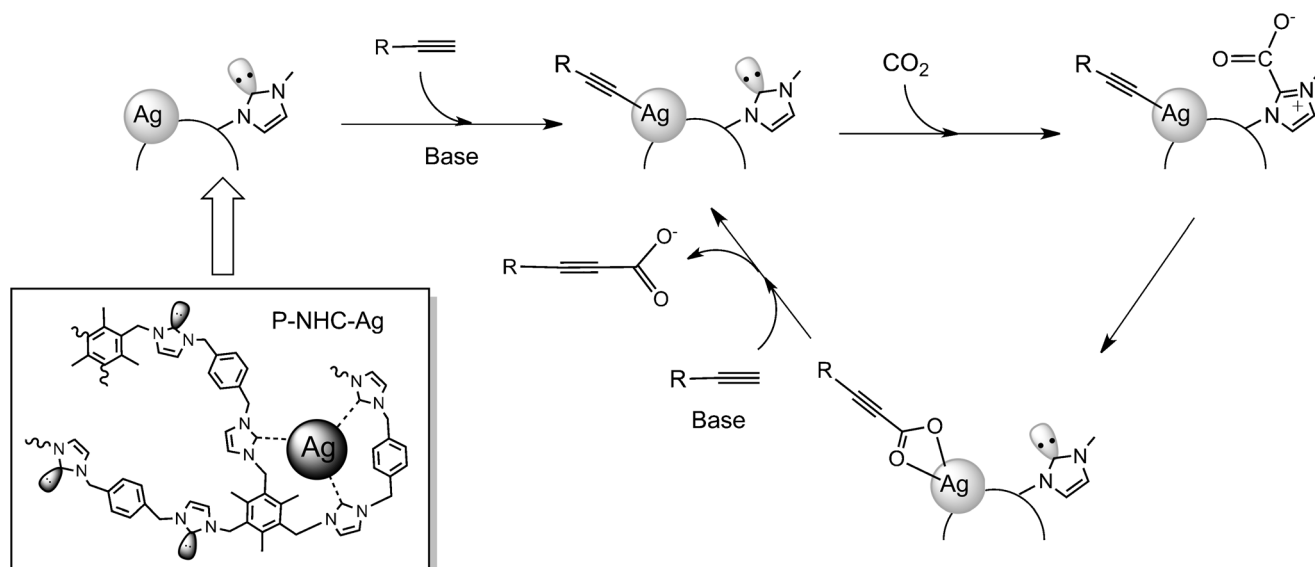
**Scheme 3.** Possible reaction mechanism for the poly-NHC-Ag nano-composite catalyzed carboxylation of terminal alkynes with $CO_2$.

form an NHC-carboxylate (Scheme 3).[39–43] The NHC-carboxylate then coordinated to a nearby silver center and this induced the nucleophilic carbanion of alkyne attacking the carboxylic carbon. Following the new C−C bond formation, the $CO_2$ unit was transferred from the carbene center to the silver center and the silver acetylide is regenerated by metathesis with alkyne. The synergistic effect between N-heterocyclic carbene polymer and silver nanoparticle greatly enhanced the catalytic activity of this nano-composite catalyst system.

In summary, we have successfully developed an N-heterocyclic carbene polymer-supported silver nanoparticle catalyst system. The novel nano-composite catalyst demonstrated very high activity and excellent stability and reusability in the carboxylation of terminal alkynes with $CO_2$ at ambient conditions. The poly-NHC-Ag catalyst exhibited excellent substrate generality and is tolerant to various functionalities. In addition, the catalyst is stable to air and can be easily recovered and reused.

## Experimental Section

### General Procedure for Carboxylation of the Terminal Alkynes (2a as Example)

Poly-NHC-Ag (5.0 mg) and $Cs_2CO_3$ (1.2 mmol) were added to DMF (5 mL) in the reaction tube (10 mL). A $CO_2$ (balloon) and 1 mmol of terminal alkynes (**1a**, 102 mg) were introduced into the reaction mixture under stirring. The reaction mixture was stirred at room temperature (about 24 °C) for 20 h. After completion of the reaction, the reaction mixture was transferred to potassium carbonate solution (2 N,

5 mL) and the mixture was stirred for 30 mins. The mixture was washed with dichloromethane (3 × 5 mL) and the aqueous layer was acidified with concentrated HCl to pH 1, then extracted with diethyl ether (3 × 5 mL). The combined organic layers were dried with anhydrous $Na_2SO_4$, filtered and the solution was concentrated in vacuum affording the pure product.

## Acknowledgements

## References

[1] M. Cokoja, C. Bruckmeier, B. Rieger, W. A. Herrmann, F. E. Kühn, *Angew. Chem.* **2011**, *123*, 8662–8690; *Angew. Chem. Int. Ed.* **2011**, *50*, 8510–8537.

[2] C. D. N. Gomes, O. Jacquet, C. Villiers, P. Thuéry, M. Ephritikhine, T. Cantat, *Angew. Chem.* **2012**, *124*, 191–194; *Angew. Chem. Int. Ed.* **2012**, *51*, 187–190.

[3] G. A. Olah, G. K. S. Prakash, A. Goeppert, *J. Am. Chem. Soc.* **2011**, *133*, 12881–12898.

[4] E. Balaraman, C. Gunanathan, J. Zhang, L. J. W. Shimon, D. Milstein, *Nature Chemistry* **2011**, *3*, 609–614.

[5] S. C. Roy, O. K. Varghese, M. Paulose, C. A. Grimes, *ACS Nano* **2010**, *4*, 1259–1278.

[6] Y. G. Zhang, S. N. Riduan, *Angew. Chem.* **2011**, *123*, 6334–6336; *Angew. Chem. Int. Ed.* **2011**, *50*, 6210–6212.

[7] T. Ohishi, L. Zhang, M. Nishiura, Z. M. Hou, *Angew. Chem.* **2011**, *123*, 8264–8267; *Angew. Chem. Int. Ed.* **2011**, *50*, 8114–8117.

[8] T. Fujihara, T. Xu, K. Semba, J. Terao, Y. Tsuji, *Angew. Chem.* **2011**, *123*, 543–547; *Angew. Chem. Int. Ed.* **2011**, *50*, 523–527.

[9] T. Sakakura, J. C. Choi, H. Yasuda, *Chem. Rev.* **2007**, *107*, 2365–2387.

[10] S. N. Riduan, Y. G. Zhang, *Dalton Trans.* **2010**, *39*, 3347–3357.

[11] S. N. Riduan, Y. G. Zhang, J. Y. Ying, *Angew. Chem.* **2009**, *121*, 3372–3375; *Angew. Chem. Int. Ed.* **2009**, *48*, 3322–3325.

[12] L. Gu, Y. G. Zhang, *J. Am. Chem. Soc.* **2010**, *132*, 914–915.

[13] T. J. Marks et al., *Chem. Rev.* **2001**, *101*, 953–996.

[14] D. J. Darensbourg, *Chem. Rev.* **2007**, *107*, 2388–2410.

[15] I. F. Boogaerts, S. P. Nolan, *J. Am. Chem. Soc.* **2010**, *132*, 8858–8859.

[16] L. Zhang, J. Cheng, T. Ohishi, Z. M. Hou, *Angew. Chem.* **2010**, *122*, 8852–8855; *Angew. Chem. Int. Ed.* **2010**, *49*, 8670–8674.

[17] D. Y. Yu and Y. G. Zhang, *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 20184–20189.

[18] D. Y. Yu and Y. G. Zhang, *Green Chem.* **2011**, *13*, 1275–1279.

[19] L. J. Gooßen, N. Rodríguez, F. Manjolinho, P. P. Lange, *Adv. Synth. Catal.* **2010**, *352*, 2913–2917.

[20] X. Zhang, W. Z. Zhang, X. Ren, L. L. Zhang and X. B. Lu, *Org. Lett.* **2011**, *13*, 2402–2405.

[21] A. Correa, R. Martin, *Angew. Chem.* **2009**, *121*, 6317–6320; *Angew. Chem. Int. Ed.* **2009**, *48*, 6201–6204.

[22] S. P. Bew, in: *Comprehensive Organic Functional Groups Transformation II*, (Eds.: A. R. Katritzky, R. J. K. Taylor), Elsevier, Oxford, **2005**, p 19.

[23] F. Lehmann, L. Lake, E. A. Currier, R. Olsson, U. Hacksell, K. Luthman, *Eur. J. Med. Chem.* **2007**, *42*, 276–285.

[24] D. Bonne, M. Dekhane, J. Zhu, *Angew. Chem.* **2007**, *119*, 2537–2540; *Angew. Chem. Int. Ed.* **2007**, *46*, 2485–2488.

[25] J. Moon, M. Jeong, H. Nam, J. Ju, J. H. Moon, H. M. Jung, S. Lee, *Org. Lett.* **2008**, *10*, 945–948.

[26] J. Moon, M. Jang, S. Lee, *J. Org. Chem.* **2009**, *74*, 1403–1406.

[27] W. Jia, N. Jiao, *Org. Lett.* **2010**, *12*, 2000–2003.

[28] W. Nagata, M. Yoshioka, *Organic Reactions*, Wiley, Hoboken, NJ, **1977**, Vol. 25, p 255.

[29] G. W. Ebert, W. L. Juda, R. H. Kosakowski, B. Ma, L. Dong, K. E. Cummings, M. V. B. Phelps, A. E. Mostafa, J. Luo, *J. Org. Chem.* **2005**, *70*, 4314–4317.

[30] G. A. Olah, B. Török, J. P. Joschek, I. Bucsi, P. M. Esteves, G. Rasul, G. K. S. Prakash, *J. Am. Chem. Soc.* **2002**, *124*, 11379–11391.

[31] S. Adimurthy, C. C. Malakar, U. Beifuss, *J. Org. Chem.* **2009**, *74*, 5648–5649.

[32] Y. Fukue, S. Oi, Y. Inoue, *J. Chem. Soc. Chem. Commun* **1994**, 2091–2091.

[33] W. Zhang, W. Li, X. Zhang, H. Zhou, X. Lu, *Org. Lett.* **2010**, *21*, 4748–4751.

[34] Y. G. Zhang, L. Zhao, P. K. Patra, D. Hu, J. Y. Ying, *Nano Today* **2009**, *4*, 13–20.

[35] M. X. Tan, Y. G. Zhang, J. Y. Ying, *Adv. Synth. Catal.* **2009**, *351*, 1390–1394.

[36] F. T. Wong, P. K. Patra, J. Seayad, Y. G. Zhang, J. Y. Ying, *Org. Lett.* **2008**, *10*, 2333.

[37] E. Barnea, M. S. Eisen, *Coord. Chem. Rev.* **2006**, *250*, 855–899.

[38] E. J. Park, S. H. Kim, S. Chang, *J. Am. Chem. Soc.* **2008**, *130*, 17268–17269.

[39] H. A. Duong, T. N. Tekavec, A. M. Arif, J. Louie, *Chem. Commun.* **2004**, 112–113.

[40] H. Zhou, W. Z. Zhang, C. H. Liu, J. P. Qu, X. B. Lu, *J. Org. Chem.* **2008**, *73*, 8039–8044.

[41] Y. Kayaki, M. Yamamoto, T. Ikariya, *Angew. Chem.* **2009**, *121*, 4258–4261; *Angew. Chem. Int. Ed.* **2009**, *48*, 4194–4197.

[42] H. Zhou, Y. M. Wang, W. Z. Zhang, J. P. Qu, X. B. Lu, *Green Chem.* **2011**, *13*, 644–650.

[43] Y. G. Zhang, J. Y. G. Chan, *Energy Environ. Sci.* **2010**, *3*, 408–417.