APPLIED ORGANOMETALLIC CHEMISTRY
Appl. Organometal. Chem. 2006; **20**: 771–774
DOI:10.1002/aoc.1139

NHC–Pd(II) complex–Cu(I) co-catalyzed homocoupling reaction of terminal alkynes

Min Shi* and Heng-xin Qian

State Key Laboratory of Organometallic Chemistry, Shanghai Institute of Organic Chemistry, Chinese Academy of Science, 354 Fenglin Lu, Shanghai 200032, People's Republic of China

Received 18 May 2006; Accepted 13 June 2006

Two NHC–Pd(II) complexes synthesized from *trans*-cyclohexane-1,2-diamine were fairly effective in the NHC–Pd(II) complex/Cu co-catalyzed terminal alkyne homocoupling reaction to give the corresponding symmetrical 1,4-disubstituted 1,3-diynes in good yields under mild conditions. Copyright © 2006 John Wiley & Sons, Ltd.

KEYWORDS: *trans*-cyclohexane-1,2-diamine; terminal alkynes; homocoupling reaction; 1,4-disubstituted 1,3-diynes

INTRODUCTION

With its unique ligating properties, *N*-heterocyclic carbenes (NHC) have long been the subject of both synthetic and catalytic studies.[1–4] Owing to the high stability of the metal complexes of NHCs toward heat, moisture and molecular oxygen (O_2), these complexes have been successfully used in a wide range of catalytic reactions,[5–32] even in oxidative reaction with molecular oxygen (O_2) as an oxidant.[33]

The palladium-catalyzed terminal alkyne dimerization, through oxidative homocoupling, is a useful approach to the synthesis of symmetrical 1,4-diynes. Reported protocols for the oxidative homocoupling reactions include: (1) use of $Pd(PPh_3)_4$, CuI, Et_3N and chloroacetone (as the reoxidant) in benzene;[34] (2) $Pd(PPh_3)_2Cl_2$, CuI, Et_3N or DABCO and bromoacetate (as the reoxidant) in THF;[35] (3) $Pd(Ph_3P)_2Cl_2$, CuI and molecular iodine (as the reoxidant) in *i*-Pr_3N;[36] (4) $Pd(dba)_2$ (dba: *E*,*E*-dibenzylidene acetone), *n*-Bu_4NBr, NaOH and allyl bromide (as the reoxidant) in CH_2Cl_2;[37] and (5) $(NHC)Pd[P(o\text{-}tol)_3]I_2$, CuI, Et_3N, molecular oxygen (O_2) in THF.[38] In all of the above cases, a stoichiometric amount of oxidant is required for successful homocoupling reactions. Owing to the inertness of the NHC–Pd(II) complexes towards oxygen and moisture, they have been used as catalysts in aerobic oxidation of alcoholes[33,39] and aerobic intramolecular Wacker-type cyclization reactions.[40] It is very convenient and economical to use molecular oxygen as the oxidant in above reactions. We report herein two novel NHC–Pd(II) complexes, derived from *trans*-cyclohexane-1,2-diamine, catalyzed homocoupling reaction of terminal alkynes under aerobic conditions.

RESULTS AND DISCUSSION

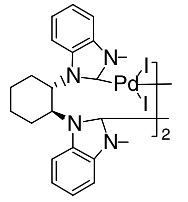
NHC–Pd(II) complexes **1** and **2** were synthesized from *trans*-cyclohexane-1,2-diamine.* The application of Pd(II)–NHC complex **1** (0.5 mol%) as a catalyst for homocoupling reaction was first tested using phenylacetylene (1.0 mmol) as substrate in the presence of the cocatalyst CuI (3.0 mol%) under ambient atmosphere in *N*,*N*-dimethylformamide (DMF) because Pd(II)–NHC complex **1** can only be partially dissolved in DMF and DMA (*N*,*N*-dimethylacetamide). The base effects were carefully examined in this homocoupling reaction. The results are summarized in Table 1. The use of K_2CO_3 as the base in DMF at 60 °C gave the corresponding coupled product 1,4-biphenyl-1,3-diyne **3a** in 15% yield after 12 h (Table 1, entry 1). Under identical conditions, **3a** was obtained in moderate yields when a series of amines were used as bases (Table 1, entries 2–9). Among these organic bases we found that in the presence of *N*-benzylethanolamine, the

---

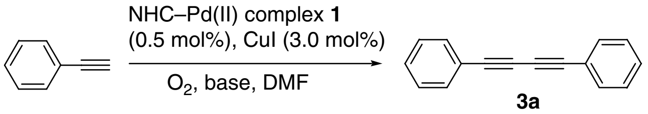
*Correspondence to: Min Shi, State Key Laboratory of Organometallic Chemistry, Shanghai Institute of Organic Chemistry, Chinese Academy of Science, 354 Fenglin Lu, Shanghai 200032, People's Republic of China.
E-mail: Mshi@pub.sioc.ac.cn
Contract/grant sponsor: State Key Project of Basic Research; Contract/grant number: 973; G2000048007.
Contract/grant sponsor: Shanghai Municipal Committee of Science and Technology.
Contract/grant sponsor: National Natural Science Foundation of China; Contract/grant number: 203900502; 20472096; 20272069.

* The synthesis of these two NHC–Pd(II) complexes **1** and **2** and their applications in Suzuki and Heck reactions have been reported. The X-ray crystal structure of NHC–Pd(II) complex **2** has been also indicated in previous literature.[41,42]

Table 1. Screening for bases in the NHC–Pd(II) complex **1**/Cu(I) catalyzed homocoupling reaction of phenylacetylene (1.0 mmol) and base (0.5 mmol) in DMF (2.0 mL) with O_2 as an oxidant



NHC–Pd(II) complex **1**



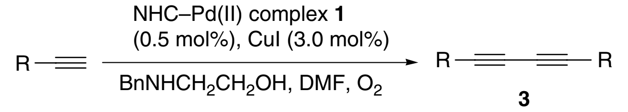
Entry	Base	Temperature (°C)	Time (h)	Yield (%)[a] 3a
1	K_2CO_3	60	12	15
2	Et_3N	60	12	50
3	DMAP	60	12	40
4	TMEDA	60	12	55
5	$PhN(CH_3)_2$	60	12	25
6	Et_2NH	60	12	58
7	HN⟨ ⟩N-CH_2CH_2OH	60	12	45
8	$(CH_3)_2NCH_2CH_2OH$	60	12	50
9	$BnNHCH_2CH_2OH$	60	12	60
10	$BnNHCH_2CH_2OH$	40	12	86
11	$BnNHCH_2CH_2OH$	80	12	45
12	$BnNHCH_2CH_2OH$	25	12	42
13[b]	$BnNHCH_2CH_2OH$	40	12	85

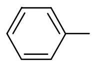
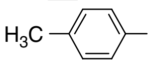
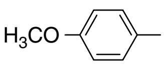
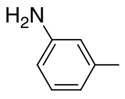
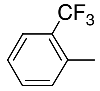
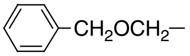
[a] Isolated yields. [b] DMA as solvent.

corresponding coupled product **3a** was obtained in higher yield (Table 1, entry 9). Next, the temperature effect on this reaction was also examined. We found that under identical conditions, the coupled product **3a** was obtained in lower yield (45%) at 80 °C after 12 h, but in higher yield at 40 °C (86%) (Table 1, entries 10 and 11). By lowering the reaction temperature further to room temperature (25 °C), **3a** was again obtained in poor yield (42%) (Table 1, entry 12). When DMA was used as solvent in this reaction at 40 °C, the coupled product **3a** was obtained in similar yield (85%) to that in DMF (86%; Table 1, entries 10 and 13).

Under these optimized reaction conditions, the homocoupling reaction of a variety of arylacetylenes was examined. The results are summarized in Table 2. As can be seen, various substituted arylacetylenes afforded the corresponding coupling products **3a–e** in moderate to good yields under ambient atmosphere within 12 h (Table 2, entries 2–5). For aliphatic acetylene, the corresponding coupling product **3f** was obtained in 60% yield (Table 1, entry 6).

Table 2. NHC–Pd(II) complex **1**/Cu(I) catalyzed homocoupling reaction of various substituted acetylenes (1.0 mmol) and base (0.5 mmol) in DMF (2.0 ml) with O_2 as the oxidant



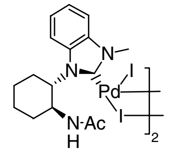
Entry	R	Temperature (°C)	Time (h)	Yield (%)[a] 3
1		40	12	**3a**, 86
2		40	10	**3b**, 90
3		40	10	**3c**, 92
4		40	10	**3d**, 82
5		40	5	**3e**, 50
6		40	24	**3f**, 60

[a] Isolated yields.

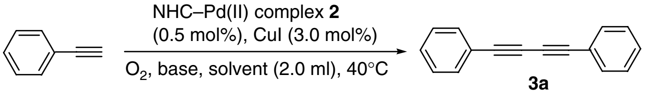
The application of Pd(II)-NHC complex **2** (0.5 mol%) as a catalyst for the homocoupling reaction of phenylacetylene (1.0 mmol) in the presence of cocatalyst CuI (3.0 mol%) was first tested under ambient atmosphere at 40 °C. The crystal structure of Pd(II)–NHC complex **2** has been disclosed by X-ray diffraction.[42] Moreover, this Pd(II)-NHC complex is soluble in a variety of solvents such as dichloromethane and acetonitrile. The base and solvent effects on this reaction were carefully examined. The results are summarized in Table 3. The use of triethylamine as the base and solvent at 40 °C gave no coupled product (Table 3, entry 1). By means of several organic solvents such as tetrahydrofuran (THF), acetonitrile (MeCN) or DMF, the corresponding coupling product 1,4-biphenyl-1,3-diyne **3a** was obtained in moderate yields after 10 h with triethylamine as the base (Table 3, entries 2–6). Among these examined conditions, **3a** was obtained in the higher yield (70%) when DMF was used as a solvent (Table 3, entry 3). By use of *N*-benzylethanolamine and tetramethylethylenediamine (TMEDA) as bases in DMF, **3a** was obtained in 72 and 87% yields, respectively (Table 3, entries 7 and 8). The best result was obtained to carry out the reaction in DMF using TMEDA as a base at 40 °C.

Under these optimized reaction conditions, the homocoupling reaction of a variety of arylacetylenes and one aliphatic acetylene was studied. The results are summarized in Table 4. As can be seen, various substituted arylacetylenes afforded coupling products **3a–e** in moderate to good yields under ambient atmosphere within 6 h (Table 4, entries 2–5). For

Table 3. Screening for bases and solvents in NHC–Pd(II) complex **2**/Cu(I) catalyzed homocoupling reaction of phenylacetylene (1.0 mmol) and base (0.5 mmol) with O_2 as the oxidant



NHC–Pd(II) complex **2**



Entry	Base	Solvent	Time (h)	Yield (%)[a] **3a**
1	Et_3N	Et_3N	10	NR
2	Et_3N	THF	10	26
3	Et_3N	DMF	10	70
4	Et_3N	DMA	10	65
5	Et_3N	CH_3CN	10	60
6	Et_3N	DMSO	10	65
7	$BnNHCH_2CH_2OH$	DMF	6	72
8	TMEDA	DMF	6	87

[a] Isolated yields. NR, not reported.

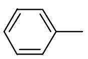
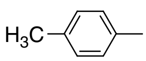
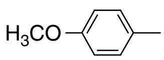
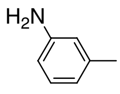
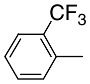
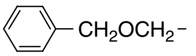
aliphatic acetylene, the corresponding coupling product **3f** was obtained in 65% yield after 24 h (Table 4, entry 6).

The structures of diyne compounds were determined by NMR spectroscopic and analytic data. One of the typical diyne product **3a** was further determined by X-ray diffraction (Fig. 1).*

Table 4. NHC–Pd(II) complex **2**/Cu(I) catalyzed homocoupling reaction of various substituted acetylenes (1.0 mmol) and base (0.5 mmol) in DMF with O_2 as the oxidant

$$R-\equiv \xrightarrow[\text{TMEDA, DMF (2.0 ml), } O_2]{\text{NHC–Pd(II) complex } \mathbf{2} \text{ (0.5 mol\%), CuI (3.0 mol\%)}} R-\equiv-\equiv-R$$

3

Entry	R	Temperature (°C)	Time (h)	Yield (%)[a] 3
1		40	6	**3a**, 87
2		40	3	**3b**, 70
3		40	3	**3c**, 78
4		40	6	**3d**, 70
5		40	5	**3e**, 42
6		40	24	**3f**, 65

[a] Isolated yields.

In conclusion, we disclosed two novel NHC-Pd(II) complexes **1** and **2** as effective catalysts for terminal alkyne homocoupling reaction in the presence of CuI under aerobic conditions. The corresponding coupled products were obtained in moderate to good yields in most cases by these two NHC–Pd(II) catalysts. Efforts are underway to elucidate the mechanistic details of this C–C bond forming reaction catalyzed by Pd(II)–NHC complex and the use of complexes **1** and **2** to catalyze other C–C bond forming transformations thereof.

Acknowledgments

We thank the State Key Project of Basic Research (project 973; no. G2000048007), Shanghai Municipal Committee of Science and Technology, and the National Natural Science Foundation of China for financial support (203900502, 20472096 and 20272069).

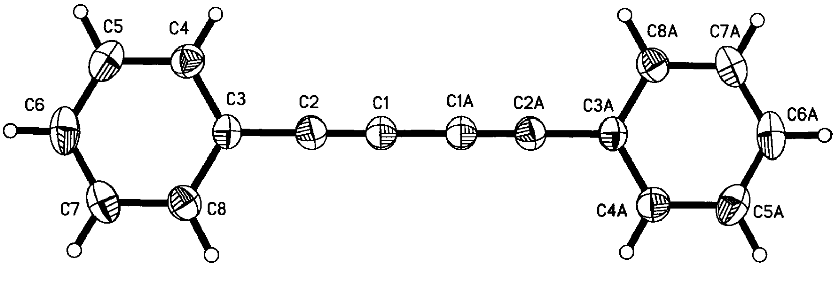


Figure 1. ORTEP drawing of **3a**.

---

* The crystal data of **3a** have been deposited in CCDC with number 258218. Empirical Formula: $C_{16}H_{10}$; formula weight: 202.24; crystal color, habit: colorless, prismatic; crystal system: monoclinic; lattice type: primitive; lattice parameters: $a = 6.6110(11)$ Å, $b = 6.0716(10)$ Å, $c = 14.627(2)$ Å, $\alpha = 90^o$, $\beta = 100.994(3)°$, $\gamma = 90°$, $V = 576.35(16)$ Å^3; space group: $P2(1)/n$; $Z = 2$; $D_{\text{calc}} = 1.165$ g/cm^3; $F_{000} = 212$; diffractometer: Rigaku AFC7R; residuals: R, Rw, 0.0600, 0.1525.

REFERENCES

1. Öfele K. *J. Organomet. Chem.* 1968; **12**: 37.
2. Wanzlick HW, Schönherr HJ. *Angew. Chem., Int. Edn Engl.* 1968; **7**: 141.
3. Arduengo III AJ, Harlow RL, Kline M. *J. Am. Chem. Soc.* 1991; **113**: 361.
4. Arduengo III AJ, Krafczyk R, Schmutzler R. *Tetrahedron* 1999; **55**: 14523.
5. Herrmann WA. *Angew. Chem. Int. Edn* 2002; **41**: 1290.
6. Herrmann WA. *Angew. Chem. Int. Edn* 1997; **36**: 2162.
7. Bourissou D, Guerret O, Gabbai FP, Betrand G. *Chem. Rev.* 2000; **100**: 39.
8. Bohm VPW, Herrmann WA. *Angew. Chem. Int. Edn* 2000; **39**: 4036.
9. Herrmann WA, Elison M, Fischer J, Kocher C, Artus GR. *J. Angew. Chem. Int. Edn* 1995; **34**: 2371.
10. Herrmann WA, Reisinger CP, Spiegler M. *J. Organomet. Chem.* 1998; **557**: 93.
11. McGuinness DS, Cavell KJ, Skelton BW, White AH. *Organo metallics* 1999; **18**: 1596.
12. Weskamp T, Bohm VPW, Herrmann WA. *J. Organomet. Chem.* 1999; **585**: 348.
13. Huang J, Nolan SP. *J. Am. Chem. Soc.* 1999; **121**: 9889.
14. Cavells KJ, McGuinness DS. *Organometallics* 2000; **19**: 741.
15. Gstottmayr CWK, Bohm VPW, Herdweek E, Grosche M, Herrmann WA. *Angew. Chem. Int. Edn* 2002; **41**: 1363.
16. Caddick S, Cloke FGN, Clentsmith GKB, Hitchcock PB, Mckeirecher D, Thcomb LR, Williams MRV. *J. Organomet. Chem.* 2001; **617–618**: 635.
17. Yang C, Nolan SP. *Synlett.* 2001; 1539.
18. Batey RA, Shen M, Lough AJ. *Org. Lett.* 2002; **4**: 1411.
19. Grasa GA, Nolan SP. *Org. Lett.* 2001; **3**: 119.
20. Hillier AC, Grasa GA, Vicin MS, Lee HM, Yang C, Nolan SP. *J. Organomet. Chem.* 2002; **653**: 69.
21. Selvakumar A, Zapf A, Beller M. *Org. Lett.* 2002; **4**: 3031.
22. Gao C-W, Tao X-C, Liu T-P, Huang J-L, Qian Y-L. *Chin. J. Chem.* 2002; **20**: 819.
23. Altenhoff G, Goddard R, Lehmann CW, Glorius F. *Angew. Chem. Int. Edn* 2003; **42**: 3690.
24. Navarro O, Kelly III RA, Nolan SP. *J. Am. Chem. Soc.* 2003; **125**: 16194.
25. Ackermann L, Furstner A, Weskamp T, Kohl FJ, Herrmann WA. *Tetrahedron Lett.* 1999; **40**: 4787.
26. Huang J, Stevens ED, Nolan SP, Petersen JL. *J. Am. Chem. Soc.* 1999; **121**: 2674.
27. Scholl M, Tranka TM, Morgan JP, Grubbs RH. *Tetrahedron Lett.* 1999; **40**: 2247.
28. Weskamp T, Kohl FJ, Hieringer W, Gleich D, Herrmann WA. *Angew. Chem. Int. Edn* 1999; **38**: 2416.
29. Frenzel U, Weskamp T, Kohl FJ, Schattenmann WC, Nuyken O, Herrmann WA. *J. Organomet. Chem.* 1999; **586**: 263.
30. Trnka TM, Grubbs RH. *Acc. Chem. Res.* 2001; **34**: 18.
31. Chatterjee AK, Grubbs RH. *Angew. Chem. Int. Edn* 2002; **41**: 3171.
32. Choi T-L, Chatterjee AK, Grubbs RH. *Angew. Chem. Int. Edn* 2001; **40**: 1277.
33. Jensen DR, Sigman MS. *Org. Lett.* 2003; **5**: 63.
34. Rossi R, Carpita A, Bigelli C. *Tetrahedron Lett.* 1985; **26**: 523.
35. Lei A, Srivastava M, Zhang X. *J. Org. Chem.* 2002; **67**: 1969.
36. Liu Q, Burton DJ. *Tetrahedron Lett.* 1997; **38**: 4371.
37. Vlassa M, Ciocan-Tarta I, Margineanu F, Oprean I. *Tetrahedron* 1996; **52**: 1337.
38. Herrmann WA, Bohm VPW, Gstottmayr CWK, Grosche M, Reisinger C-P, Weskamp T. *J. Organomet. Chem.* 2001; **617–618**: 616.
39. Mueller JA, Goller CP, Sigaman MS. *J. Am. Chem. Soc.* 2004; **126**: 9724.
40. Muniz K. *Adv. Synth. Catal.* 2004; **346**: 1425.
41. Shi M, Qian H-X. *Tetrahedron* 2005; **61**: 4949.
42. Shi M, Qian H-X. *Appl. Organomet. Chem.* 2005; **19**: 1083.
43. Campbell ID, Eglington G. *Org. Synth.* 1973; **5**: 517.
44. Uchida A, Nakazawa T, Kondo I, Iwata N, Matsuda S. *J. Org. Chem.* 1972; **37**: 3749.
45. Tretyakov EV, Knight DW, Vasilevsky SF. *J. Chem. Soc., Perkin Trans. I* 1999; **24**: 3713.

DOI: 10.1002/aoc