http://dx.doi.org/10.5012/bkcs.2012.33.9.3133

# Facile Synthesis of 4,7-Disubstituted Conjugation-Extended 1,10-Phenanthrolines

**Hyungsock Suh, Fernando Hung-Low,† Dominick Casadonte,† Han-je Kim,‡ Beomsik Kim, and Taesun Chang***

*Environment & Resource Research Center, KRICT (Korea Research Institute of Chemical Technology), Daejeon 305-600, Korea*
**E-mail: tschang@krict.re.kr*
*†Department of Chemistry & Biochemistry, Texas Tech University, Lubbock, TX, 79405, USA*
*‡Department of Science Education, Gongju National University of Education, Gongju 314-711, Korea*
*Received May 22, 2012, Accepted June 22, 2012*

**Key Words :** Cross-coupling, Phenanthroline, Substitution, Alkynes, Conjugation

1,10-Phenanthroline (phen) is a ubiquitous ligand for the chelation of transition metals.[1] Phenanthroline derivatives are precursors for a variety of functional materials, including water splitting catalysts,[2] organic-inorganic hybrid materials,[3] functionalized metal complexes,[4] catalysts for organic synthesis,[5] magnetic materials,[6] electron transfer reagents,[7] light-induced hydrogen production catalysts,[8] and light-emitting devices.[9] Substituted 1,10-phenanthroline complexes are also used in the generation of bio-active materials,[10] in bio-imaging,[11] and in DNA intercalation.[12] Most 1,10-phenanthroline complexes containing metals are colored, due to the presence of either metal-to-ligand (MLCT) or ligand-to-metal (LMCT) charge-transfer electronic transitions.[13]

The rigid, conjugated nature of the phenanthroline ligand provides opportunities for the development of extended π-networks with one-, two-, or three-dimensional structures. The use of phenanthrolines as templates for novel materials has stimulated research into the preparation of phen ligands with unique substitution and conjugation patterns. Historically, most of the substitution of 1,10-phenanthroline has occurred at the 2 and 9 positions, because they are easy to modify from the phen starting material. Recently, one group synthesized 4,7-diethynyl phenanthroline using 4,7-dicarbaldehyde phenanthroline precursor.[14] But this precursor material is too expensive to become a largely available. We are aware of one group that has synthesized a 4-substituted conjugated 1,10-phenanthroline using a ruthenium-complexed Sonogashira coupling, but, to our knowledge, uncomplexed 4,7-disubstituted conjugation-extended ligands have not been made.[15] This paucity can be attributed to the difficulties in the synthesis and purification as well as the low solubility of the final products.

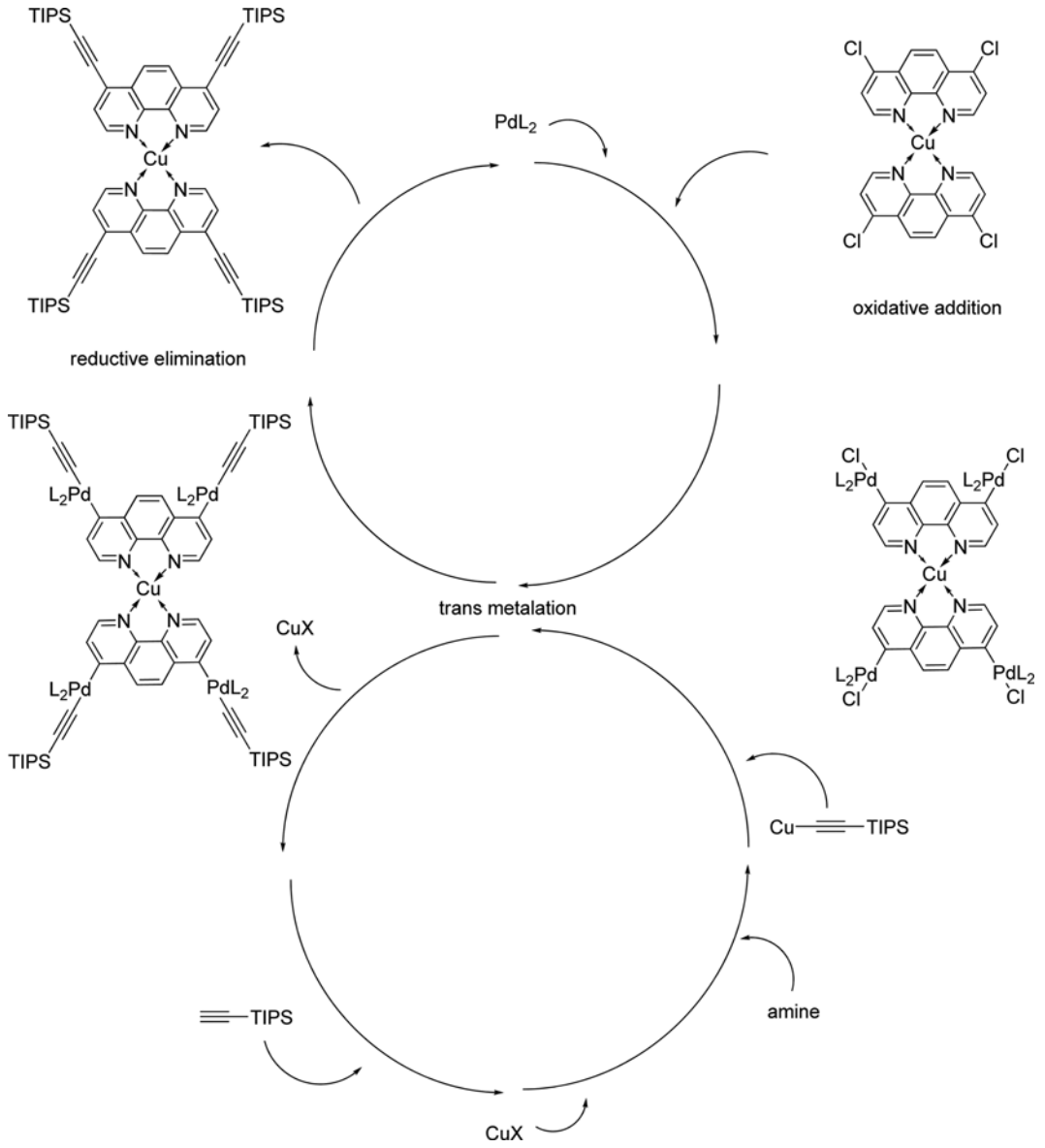
We have synthesized a series of conjugated 4,7-substituted 1,10-phenanthroline ligands through Sonogashira coupling, using 4,7-dichlorophen as a much cheaper starting material. This represents a significant advancement in profitable process with regard to backside substitution of the phenanthroline. Moreover, it opens the practical possibility for a variety of π-conjugated electro-optic and bio-inspired materials.

Success in the synthesis of the 4,7-disubstituted phen occurred through modification of the amount of catalytic copper that was added to the reaction. The general Sonogashira coupling reaction requires 5 mol % of a Pd catalyst and 10 mol % of a Cu(I) co-catalyst.[16] For successful synthesis of the 4,7-disubstituted phenanthroline ligands, the concentration of the copper co-catalyst was increased to 60 mol %. If the concentration of the Cu(I) co-catalyst were increased beyond this amount, the reactivity for the formation of the 4,7-disubstituted ligands were decreased. A proposed mechanism for the Cu(I)-facilitated Pd coupling reaction is shown in Scheme 1.

Copper (I) iodide is first chelated to the nitrogen atoms on the phen, resulting in a Cu(I) $(phen)_2$ structure followed by changing color dark red. Based on stoichiometry, 50 mol % of the Cu(I) will chelate with the phenanthroline present in the bis(phen) complexes. The remaining 10 mol % of the Cu(I) (which is the equilibrium amount necessary for the general Sonogashira coupling reaction) will function as a co-catalyst. If more than 60 mol % of Cu(I) is used, the excess mol % after chelation competes with the Pd(II) catalyst, resulted in poor coupling reactivity. The Pd oxidative addition step is regarded as the rate-determination step. Once the Pd catalyst inserts into the 4-position of the phenanthroline, the second Pd(II) catalyst quickly inserts at the 7-position, inhibiting the formation of the mono substituted product. Representative yields for 4,7-disubstituted phenanthrolines starting with 1,10-phenanthroline and 2,9-dimethyl-1,10-phenanthroline (dmp) are shown in Table 1. The yields were greater than 75% for the acetylene and phenyl acetylene derivatives. The lower yields for the tri-isopropylsilyl (TIPS) acetylene derivatives are due to significant decomposition of TIPS protecting group.

X-ray quality crystals for compounds **2a** and **3a** were prepared, and single X-ray diffraction data were collected at 150 K on a Bruker Apex II using Mo Kα (λ = 0.71073 Å) (molecular structures of compounds are shown in Figures 1 and 2). All structures were solved by direct methods after correction of the data using SADABS. All data were processed using Bruker AXS SHELXTL software, version 6.10. Hydrogen atoms were placed in calculated positions and all non-hydrogen atoms were refined anisotropically. One of the phenyl groups in compound **3a** was disordered and was modeled over two positions. Corresponding anisotropic displacement parameters were restrained to be similar.

All of the X-ray structures were in agreement with the anticipated structures. The molecules are planar, as expect-




**Scheme 1.** Proposed mechanism for the copper complexed Sonogashira coupling.

ed, due to the extended π conjugation. The molecular structure diagram for **2a** shows that the two alkynes are attached at the 4 and 7 positions of the phenanthroline.

The unit cell contains π-stacked phenanthrolines that are in an *anti*-conformation with regard to the alkyne units. A small torsional angle (4°) between the two alkynes is due to nitrogen-alkyne intermolecular hydrogen bonding.

One nitrogen is attached to the upper layer of an alkyne hydrogen, and the other nitrogen is attached to the lower layer of another alkyne hydrogen. The crystal color is brown, which may be due to the small conjugation between the two nitrogens and the two intermolecular alkynes.

The molecular structure diagram for **3a** clearly shows the attachment of the two phenylacetylenes at the 4 and 7 positions. The extended π conjugation of this molecule is reflected in the fact that the phenyl rings are almost planar to the phenanthroline, with a 16° torsional angle between **N1** and the phenyl ring, and 15° and 18° torsional angles between **N2** and the respective phenyl rings. The phenylethynyl substituents exhibit 16° and 17° torsional angles, presumably caused by packing forces on the disordered phenyl group (see Supporting Material). The presence of π stacking and solvent-phenanthroline hydrogen bonding interactions appear to be essential to the crystallization process.

**Table 1.** Yields for 4,7-disubstituted phenanthrolines

| Entry | Phen[a] | R | Yield (%)[b] |
|---|---|---|---|
| **1a** | phen | TIPS acetylene | 25 |
| **1b** | dmp | TIPS acetylene | 30 |
| **2a** | phen | acetylene | 90 |
| **2b** | dmp | acetylene | 91 |
| **3a** | phen | phenylacetylene | 78 |
| **3b** | dmp | phenylacetylene | 75 |

[a]dmp = 2,9-dimethyl-1,10-phenanthroline. [b]isolated yield of products

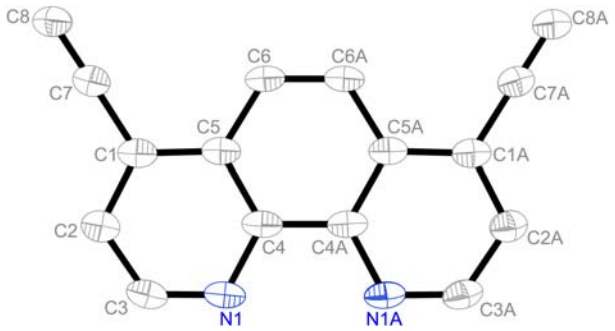



**Figure 1.** Molecular structure of **2a** with 30% probability ellipsoids. Hydrogen atoms are omitted for clarity.

The preparation of 4,7-substituted phenanthroline molecules through the simple synthetic techniques described here provides opportunities for the synthesis of a wide variety of backside-substituted phenanthroline ligands with interesting photophysical and structural characteristics. We are currently exploring some of these.

Crystal structures **2a** and **3a** have been deposited at the Cambridge Crystallographic Data Centre and allocated the deposition numbers CCDC 827894 and 827895.

## Experimental Section

**Synthesis.**

**Compound 1a:** 0.30 g (1.2 mmol) of 4,7-dichloro-1,10-phenanthroline, 0.48 g (2.2 eq.) of triisopropylsilyl acetylene, 0.05 g (0.05 eq.) of (dppf)$PdCl_2 \cdot CH_2Cl_2$, 0.24 g (2 eq.) of triethylamine, and 0.14 g (0.6 eq.) of copper iodide were suspended in 10 mL of benzene. This suspension was refluxed for 72 hours under argon. 10 mL of a 10% aqueous KCN solution and 10 mL dichloromethane were then added and the resulting mixture was stirred for 30 min at room temperature. The organic layer was extracted with 50 mL of dichloromethane twice and washed with water three times. The solvent was then evaporated and the solid was purified by column chromatography ($Al_2O_3$, DCM:MeOH = 100:1, $R_f$ = 0.4. The middle of the three bands contains the desired product) to obtain a viscous liquid (0.16 g, 25%). $^1$H NMR (300 MHz, $CDCl_3$) δ 9.12 (d, 2H), 8.38 (s, 2H), 7.74 (d, 2H), 1.25-1.21 (m, 42H). $^{13}$C NMR (75 MHz, $CDCl_3$) δ 149.71, 146.11, 129.96, 128.48, 126.13, 125.04, 102.63, 102.08, 18.70, 11.28. MS: 541.5 (M, 10%), 303 (M-TIPSMe, 40%), 229 (M-2TIPS, 80%), 73 (TIPS-Me, 100%).

**Compound 2a:** 0.30 g (0.55 mmol) of (**1a**) and 0.36 g (2.5 eq.) of tetrabutylammonium fluoride were added to 10 mL of THF. The mixture was stirred for 30 min at room temperature. 10 mL of water was added and the organic layer was extracted with 50 mL of dichloromethane twice. The product was washed with 50 mL of water twice and the solvent was then evaporated. The solid was purified by alumina column chromatography (dichloromethane and gradient with methanol; the middle of the three bands is the desired product) to obtain an ivory solid (0.11 g, 90%). $^1$H NMR (300 MHz, $CDCl_3$) δ 9.17 (d, 2H), 8.38 (s, 2H), 7.78 (d, 2H), 3.74 (s, 6H). $^{13}$C NMR (75 MHz, $CDCl_3$) δ 149.81, 146.09, 128.79, 128.63, 126.41, 125.02, 86.98, 79.17. MS: 228.1 (M, 100%).

## References


1. (a) Knight, T. E.; Goldstein, A. P.; Brennaman, M. K.; Cardolaccia, T.; Pandya, A.; DeSimone, J. M.; Meyer, T. J. *J. Phys. Chem. B* **2011**, *115*, 64. (b) Patrocinio, A. O. T.; Brennaman, M. K.; Meyer, T. J.; Iha, N. Y. M. *J. Phys. Chem. A* **2010**, *114*, 12129.
2. Arachchige, S. M.; Brown, J. R.; Chang, E.; Jain, A.; Zigler, D. F.; Rangan, K.; Brewer, K. J. *Inorg. Chem.* **2009**, *48*, 1989.
3. (a) Han, Q.; Ma, P.; Zhao, J.; Wang, Z.; Yang, W.; Guo, P.; Wang, J.; Niu, J. *Crystal Growth & Design* **2011**, *11*, 436. (b) Niu, J.; Chen, G.; Zhao, J.; Yu, C.; Ma, P.; Wang, J. *Crystal Growth & Design* **2010**, *10*, 4689.
4. Tchouka, H.; Meetsma, A. Browne, W. R. *Inorg. Chem.* **2010**, *49*, 10557.
5. (a) Giri, R.; Hartwig, J. F. *J. Am. Chem. Soc.* **2010**, *132*, 15860. (b) Simmons, E. M.; Hartwig, J. F. *J. Am. Chem. Soc.* **2010**, *132*, 17092.
6. (a) Marino, N.; Ikotun, O. F.; Julve, M.; Lloret, F.; Cano, J.; Doyle, R. P. *Inorg. Chem.* **2011**, *50*, 378. (b) Vallejo, J.; Castro, I.; Ferrando-Soria, J.; Deniz-Hernandez, M. P.; Ruiz-Perez, C.; Lloret, F.; Julve, M.; Ruiz-Garcia, R.; Cano, J. *Inorg. Chem.* **2011**, *50*, 2073.
7. (a) Warren, J. J.; Tronic, T. A.; Mayer, J. M. *Chem. Rev.* **2010**, *110*, 6961. (b) Mayer, J. M. *Acc. Chem. Res.* **2011**, *44*, 36.
8. (a) Ozawa, H.; Sakai, K. *Chem. Commun.* **2011**, *47*, 2227. (b) Tanaka, S.; Masaoka, S.; Yamauchi, K.; Annaka, M.; Sakai, K. *Dalton Trans.* **2010**, *39*, 11218.
9. Costa, R. D.; Orti, E.; Bolink, H. J.; Graber, S.; Housecroft, C. E.; Constable, E. C. *Chem.Commun.* **2011**, *47*, 3207.
10. (a) Li, C.; Sato, K.; Monari, S.; Salard, I.; Sola, M.; Banfield, M. J.; Dennison, C. *Inorg. Chem.* **2011**, *50*, 482. (b) Roy, S.; Saha, S.; Majumdar, R.; Dighe, R. R.; Jemmis, E. D.; Chakravarty, A. R. *Dalton Trans.* **2011**, *40*, 1233.
11. (a) Matson, M.; Svensson, F. R.; Norden, B.; Lincoln, P. *J. Phys. Chem. B* **2011**, *115*, 1706. (b) Svensson, F. R.; Abrahamsson, M.; Stromberg, N.; Ewing, A. G.; Lincoln, P. *J. Phys. Chem. Lett.* **2011**, *2*, 397.
12. (a) Ramakrishnan, S.; Suresh, E.; Riyasdeen, A.; Akbarsha, M. A.; Palaniandavar, M. *Dalton Trans.* **2011**, *40*, 3245. (b) Mulyana, Y.; Weber, D. K.; Buck, D. P.; Motti, C. A.; Collins, J. G.; Keene, F. R. *Dalton Trans.* **2011**, *40*, 1510. (c) Keene, F. R. *Dalton Trans.* **2011**, *40*, 2405.
13. Casadonte, D. J.; McMillin, D. R. *J. Am. Chem. Soc.* **1987**, *109*, 331.
14. Brusilowskij, B.; Schalley, C. A.; *Eur. J. Org. Chem.* **2011**, 469-477.
15. Glazer, E. C.; Magde, D.; Tor, Y. *J. Am. Chem. Soc.* **2007**, *129*, 8544.
16. Sonogashira, K.; Tohda, Y.; Hagihara, N. *Tetrahedron Lett.* **1975**, *16*, 4467.