J|A|C|S
COMMUNICATIONS

Versatile Synthesis of Pentalene Derivatives via the Pd-Catalyzed Homocoupling of Haloenynes

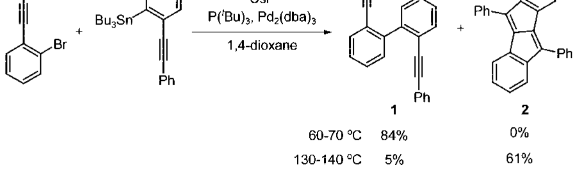
Zerubba U. Levi and T. Don Tilley*

Department of Chemistry, University of California at Berkeley, Berkeley, California 94720

Received December 19, 2008; E-mail: tdtilley@berkeley.edu

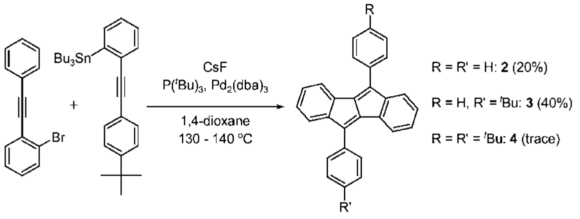
Compared to other carbocyclic frameworks, pentalene (C_8H_6) and derivatives thereof have received relatively sparse attention despite their intriguing properties as ligands[1−4] and electroactive materials.[5−12] The difficulty associated with exploring these compounds is usually attributed to the lack of general, efficient synthetic routes to the pentalene framework. Formally an 8π *anti*-aromatic system, the unsubstituted molecule C_8H_6 is thermally unstable and dimerizes above −196 °C. Pentalene substituents can provide greater stability, via steric or electronic effects, as observed for hexaphenylpentalene,[13] 1,3-bis (dimethylamino)pentalene,[14] and 1,3,5-tri-*tert*-butylpentalene.[8] Katz and co-workers demonstrated that pentalene can be stabilized by coordination to metals centers,[15] and bimetallic complexes with bridging pentalene ligands have been shown to exhibit interesting electronic properties and strong electronic coupling between metal centers.[11,16] Thus, pentalenes represent promising ligands for the construction of extended sandwich complexes and other advanced materials. Pentalene is typically produced via the flash vacuum pyrolysis of cyclooctatetraene at 400−675 °C.[2] Nonpyrolytic routes to pentalene have been reported, such as the Skatteböl rearrangement of a geminal dibromocyclopropane-fused cycloheptatriene,[2] but there are no general methods for the synthesis of substituted pentalenes. Dibenzopentalenes exhibit enhanced stability relative to the parent pentalenes, but their syntheses still necessitate pyrolysis[17] or multistep procedures that are incompatible with controlled substitution.[18] This report describes a relatively simple synthetic route to a variety of pentalene derivatives, via a Pd-catalyzed reductive homocoupling of haloenynes.

A general interest in oligo(alkynylphenylene)s[19] as precursors to π-conjugated systems with new electronic properties led to the attempted synthesis of 2,2′-bis(phenylethynyl)biphenyl (**1**) using the protocol of Littke and Fu[20] for Pd-catalyzed C−C couplings to hindered, substituted biphenyls (eq 1). At moderate temperatures (60−70 °C) **1** was obtained in good yield. However, attempts to optimize the reaction conditions revealed that, at more elevated temperatures (130−140 °C), the major product was instead the dibenzopentalene **2**. Furthermore, **1** is stable at the higher temperatures and did not transform to **2** under the reaction conditions at 140 °C over 24 h. Thus, **1** is not a precursor to **2**.



(1)

To determine whether or not these products result exclusively from cross-coupling reactions, the crossover experiment of eq 2 was conducted, and the product distribution was determined by GC−MS. While significant quantities of the cross product **3** were observed, homocoupling of the aryl bromide to yield **2** also occurs under the high temperature conditions. Only trace quantities of the aryl stannane homocoupled product **4** were observed (no diyne was observed by GC−MS). Thus, the bromide reactant is more active, and these results indicated that the pentalene derivatives might be accessible via single substrates of this type. Such couplings would seem to require the addition of a reductant to facilitate a reaction that is catalytic in Pd.



(2)

Recent reports have described the Pd-catalyzed homocoupling of aryl halides with reducing agents such as zinc,[22] indium,[23] hydrogen gas,[24] formate salts,[25] hydroquinone,[26] alcohols,[27] and amines.[28] Screening of various reaction conditions with such reductants revealed that the highest yields of dibenzopentalene (>80%) were obtained in the presence of 2 equiv of hydroquinone and Cs_2CO_3 (entry 1, Table 1). Consistent with reports on Pd-catalyzed Ullmann couplings,[22,24,25,27] small amounts (typically <5%) of the hydrodehalogenated product were obtained as side products. The optimized reaction conditions are compatible with trimethylsilyl groups (entry 3), alkynes, and trifluoromethyl substituents (entry 4 and Figure 1).

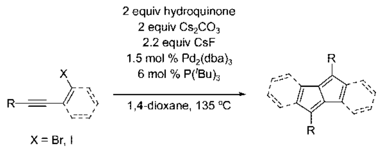
Given the interest in thienoacenes and other fused heterocyclic aromatic structures,[29,30] the possibility of constructing thienylpentalene derivatives was explored. The precursor 3-bromo-4-phenylethynylthiophene was prepared according to the literature[31] and subjected to the high temperature coupling conditions (entry 5). The desired dithienylpentalene was formed, albeit in moderate yields. To extend the methodology beyond annulated pentalenes, simple haloenynes were explored as substrates. Such enynes are readily accessible via a variety of synthetic methods[31,32] and prove to be viable substrates in the pentalene coupling reaction (entry 6; Figure 1). However, in this demanding coupling, the alkenyl iodide provided significantly higher yields (60%) relative to the alkenyl bromide (20%); again, this result is consistent with reports on Pd-catalyzed Ullmann couplings.[25,26]

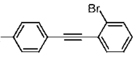
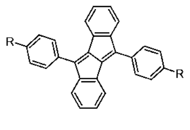
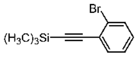
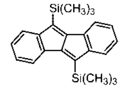
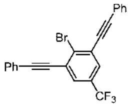
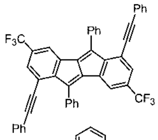
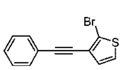
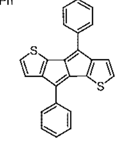
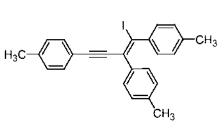
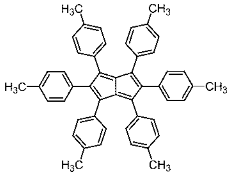
The high temperature coupling reaction was not affected by proton sponge (1 equiv), radical trap (1 equiv of TEMPO or dihydroanthracene), or radical initiator (1 equiv of AIBN). Furthermore, no reaction was observed in the absence of a Pd precatalyst.

The observed change in chemoselectivity as a function of temperature suggests a drastic change in the nature of the catalyst

10.1021/ja809930f CCC: $40.75

Table 1. Synthesis of Pentalene Derivatives via the Reductive Homocoupling of Aryl and Alkenyl Halides Catalyzed by Palladium



Entry	Halide	Product	Yield (%)[a]
1: R = H 2: R = ^{t}Bu			**2**, R = H: 88 **4**, R = ^{t}Bu: 85
3[b]			**5**, 83
4			**6**, 72
5			**7**, 55
6			**8**, 60

[a] Isolated yields. [b] CsF was not used.

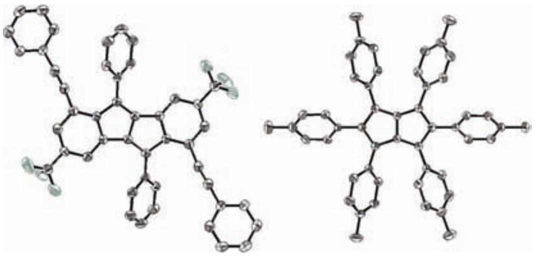


Figure 1. ORTEP diagram of **6** (on left) and **8** (on right), with thermal ellipsoids at 50% probability.

with temperature. Consistent with other observations of Pd-catalyzed coupling reactions at high temperatures,[33,34] these reaction conditions produce significant quantities of Pd nanoparticles (as evident by *in situ* TEM analysis; Figure S1). Thus, preliminary results suggest that the active catalyst in these new coupling reactions is nanometallic Pd. The mechanism of this coupling may involve an initial oxidative addition of the haloenyne, followed by an intermolecular carbopalladation of a second equivalent of the haloenyne, with a subsequent intramolecular carbopalladation to assemble one ring of the pentalene system (Scheme S1). An intramolecular oxidative addition to the aryl halide and reductive elimination would yield the pentalene, and a two-electron reduction of a Pd(II) intermediate would make the process catalytic in Pd.

In summary, a novel Pd-catalyzed coupling reaction which constitutes a versatile new route to pentalene derivatives has been discovered. This method represents a substantial simplification over previous syntheses of substituted pentalenes. Ongoing studies are focused on application of this methodology to the synthesis of related bicyclic species and to determination of the mechanism of this process.

Acknowledgment. The authors gratefully acknowledge the support of the NSF (Research Grant No. CHE0314709) and the Director, Office of Energy Research, Office of Basic Energy Sciences, Chemical Sciences Division of U.S. DOE under Contract DE-AC02-05CH11231. We also thank Dr. Antonio DiPasquale of the CHEXRAY X-ray crystallography facility at U.C. Berkeley for obtaining the crystal structure of **8**.

Supporting Information Available: Experimental details, *in situ* TEM images, and Scheme S1. This material is available free of charge via the Internet at http://pubs.acs.org.

References

(1) Bendjaballah, S.; Kahlal, S.; Costuas, K.; Bévillon, E.; Saillard, J.-Y. *Chem.—Eur. J.* **2006**, *12*, 2048–2065.
(2) Summerscales, O. T.; Cloke, F. G. N. *Coord. Chem. Rev.* **2006**, *250*, 1122–1140.
(3) Cloke, F. G. N. *Pure Appl. Chem.* **2001**, *73*, 233–238.
(4) Balazs, G.; Cloke, F. G. N.; Harrison, A.; Hitchcock, P. B.; Green, J.; Summerscales, O. T. *Chem. Commun.* **2007**, 873–875.
(5) Willner, I.; Becker, J. Y.; Rabinovitz, M. *J. Am. Chem. Soc.* **1979**, *101*, 395–401.
(6) Rabinovitz, M.; Willner, I.; Minsky, A. *Acc. Chem. Res.* **1983**, *16*, 298–304.
(7) Saito, M.; Nakamura, M.; Tajima, T. *Chem.—Eur. J.* **2008**, *14*, 6062–6068.
(8) Johnson, R. W. *J. Am. Chem. Soc.* **1977**, *99*, 1461–1465.
(9) Bally, T.; Chai, S.; Neuenschwander, M.; Zhu, Z. *J. Am. Chem. Soc.* **1997**, *119*, 1869–1875.
(10) Oelckers, B.; Cháez, I.; Manríquez, J. M. *Organomet.* **1993**, *12*, 3396–3397.
(11) Jones, S. C.; Hascall, T.; Barlow, S.; O'Hare, D. *J. Am. Chem. Soc.* **2002**, *124*, 11610–11611.
(12) Kertesz, M. *Macromolecules* **1995**, *28*, 1475–1480.
(13) Goff, E. L. *J. Am. Chem. Soc.* **1962**, *84*, 3975–3976.
(14) Hafner, K.; Bangert, K. F.; Orfanos, V. *Angew. Chem., Int. Ed. Engl.* **1967**, *6*, 451.
(15) Knox, S. A. R.; Stone, F. G. A. *Acc. Chem. Res.* **1974**, *7*, 321–328.
(16) Bunel, E. E.; Valle, L. *J. Am. Chem. Soc.* **1988**, *110*, 6596–6598.
(17) Brown, R. F. C.; Eastwood, F. W.; Wong, N. R. *Tetrahedron Lett.* **1993**, *34*, 3607.
(18) Yang, J.; Lakshmikantham, M. V.; Cava, M. P. *J. Org. Chem.* **2000**, *65*, 6739–6742.
(19) Breen, C. A.; Tischler, J. R.; Bulovíc, V.; Swager, T. M. *Adv. Mater.* **2005**, *17*, 1981–1985.
(20) Littke, A. F.; Schwarz, L.; Fu, G. C. *J. Am. Chem. Soc.* **2002**, *124*, 6343–6348.
(21) Hassan, J.; Sévignon, M.; Gozzi, C.; Schulz, E.; Lemaire, M. *Chem. Rev.* **2002**, *102*, 1359–1469.
(22) Li, J.-H.; Xie, Y.-X.; Yin, D.-L. *J. Org. Chem.* **2003**, *68*, 9867–9869.
(23) Chang, Y. M.; Lee, S. H.; Cho, M. Y.; Yoo, B. W.; Rhee, H. J.; Lee, S. H.; Yoon, C. M. *Synth. Commun.* **2005**, *35*, 1851–1857.
(24) Mukhopadhyay, S.; Rothenberg, G.; Wiener, H.; Sasson, Y. *Tetrahedron* **1999**, *55*, 14763–14768.
(25) Abiraj, K.; Srinivasa, G. R.; Gowda, D. C. *Tetrahedron Lett.* **2004**, *45*, 2081–2084.
(26) Ma, N.; Duan, Z.; Wu, Y. *J. Organomet. Chem.* **2006**, *691*, 5697–5700.
(27) Hassan, J.; Penalva, V.; Lavenot, L.; Gossi, C.; Lemaire, M. *Tetrahedron* **1998**, *54*, 13793–13804.
(28) Park, S. B.; Alper, H. *Tetrahedron Lett.* **2004**, *45*, 5515–5517.
(29) Brusso, J.; Hirst, O.; Dadvand, A.; Ganesan, S.; Cicoira, F.; Robertson, C. M.; Oakley, R. T.; Federico, R.; Perepichka, D. F. *Chem. Mater.* **2008**, *20*, 2484–2494.
(30) Yan, Q.; Zhou, Y.; Ni, B.-B.; Ma, Y.; Wang, J.; Pei, J.; Cao, Y. *J. Org. Chem.* **2008**, *73*, 5328–5339.
(31) Martin, R.; Marta, R. R.; Buchwald, S. L. *Angew. Chem., Int. Ed.* **2006**, *45*, 7079–7082.
(32) Liu, Y.; Zhong, Z.; Nakajima, K.; Takahashi, T. *J. Org. Chem.* **2002**, *67*, 7451–7456.
(33) Reets, M. T.; Westermann, E. *Angew. Chem., Int. Ed.* **2000**, *39*, 165–168.
(34) de Vries, J. G. *Dalton Trans.* **2006**, 421–429.

JA809930F