A Novel Palladium-Catalyzed Synthesis of Phenanthrenes from *ortho*-Substituted Aryl Iodides and Diphenyl- or Alkylphenylacetylenes
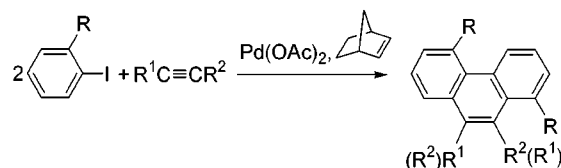
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ABSTRACT

1,5-Selectively disubstituted 9,10-diphenyl- or alkylphenylphenanthrenes are obtained by reaction of *ortho*-substituted aryl iodides and diphenyl- or alkylphenylacetylenes in the presence of palladium and norbornene as catalysts. The reaction outcome is controlled by the steric effect exerted by the *ortho* substituent in the aryl iodide.

Selective aromatic functionalization is an important goal of organic chemistry.[1] We previously reported palladium-catalyzed procedures leading to selectively alkylated aromatics.[2] A recent report also describes an interesting extension to condensed ring formation.[3] We have now worked out a new and selective aromatic arylation leading to substituted phenanthrenes. The present synthesis stems from the observation that two molecules of an *ortho*-substituted aryl iodide react with palladium(0) in the presence of norbornene to give a palladium-bonded biphenylyl **1**. The reaction could be made catalytic by ring closure with diphenyl- or alkylphenylacetylenes[4] to form 1,5-disubstituted 9,10-diphenyl- or alkylphenylphenanthrenes **2** and **2a** (Scheme 1).

Thus by heating an *ortho*-substituted aryl iodide (2 equiv), diphenylacetylene (1 equiv), potassium carbonate (3 equiv),

Scheme 1
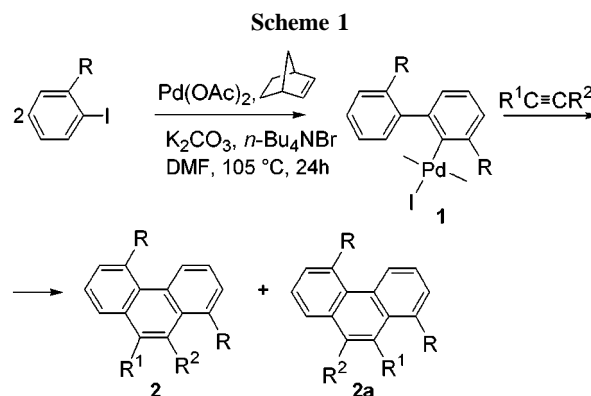
and tetrabutylammonium bromide (6 equiv) in DMF for 24 h at 105 °C with palladium acetate (0.05 equiv) and norbornene (0.5 equiv) as catalysts under nitrogen, satisfactory yields of **2** (R^1, R^2 = Ph) were obtained.[5] The conditions used result from examination of the effect of various parameters on the yield of the phenanthrene derivative. We found that the addition of tetrabutylammonium bromide (up

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(3) Lautens, M.; Piguel, S. *Angew. Chem., Int. Ed.* **2000**, *39*, 1045.

			yield (%)[b]	
run	R in 2-RC$_6$H$_4$I	R^1 and R^2 in R^{1}C≡CR^2	2	2a
1	Me	R^1, R^2 = Ph	82	
2	Et	R^1, R^2 = Ph	85	
3	*n*-Pr	R^1, R^2 = Ph	83	
4	*i*-Pr	R^1, R^2 = Ph	93	
5	*n*-Bu	R^1, R^2 = Ph	84	
6	*t*-Bu		*c*	
7	OMe	R^1, R^2 = Ph	64[d]	
8	CH$_2$OMe	R^1, R^2 = Ph	51[d]	
9	CO$_2$Me	R^1, R^2 = Ph	33[d]	
10	*i*-Pr	R^1, R^2 = 4-MeOC$_6$H$_4$	80	
11	*i*-Pr	R^1 = Ph; R^2 = 4-CF$_3$C$_6$H$_4$	19	55
12	*i*-Pr	R^1 = Ph; R^2 = Me	32	11[e]
13	*i*-Pr	R^1, R^2 = *n*-Pr	*f*	

[a] Reaction conditions: 5 mol % Pd(OAc)$_2$, 2 equiv of aryl iodide, 1 equiv of diphenylacetylene, 3 equiv of K$_2$CO$_3$, 6 equiv of *n*-Bu$_4$NBr, and 0.5 equiv of norbornene in DMF at 105 °C for 24 h. [b] Isolated yield on the aryl iodide. [c] Compound **9** (Scheme 4) is formed in 78% yield. [d] Ten mole percent Pd(OAc)$_2$. [e] Compound **3** (Scheme 2) is also obtained in 41% yield. [f] Compound **4** (Scheme 2) is isolated in 84% yield.

to 3 equiv per equiv of aryl iodide) increased the yield dramatically, whereas the corresponding chloride salt as well as LiCl were inactive.[4b,6] With tetrabutylammonium bromide and K$_2$CO$_3$ as a base good results were achieved; by contrast a low selectivity was obtained both with Cs$_2$CO$_3$ and AcOK. The solvent of choice turned out to be DMF; the use of DMA and acetonitrile gave poor yields. To obtain a satisfactory conversion in DMF a temperature as high as 105 °C was required.

Table 1 reports the isolated yields of products **2** and **2a** with different R, R^1, and R^2.

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(5) **General procedure** for the case of 2-*n*-butyliodobenzene and diphenylacetylene. A mixture of Pd(OAc)$_2$ (4 mg, 0.018 mmol), K$_2$CO$_3$ (150 mg, 1.08 mmol), *n*-Bu$_4$NBr (696 mg, 2.16 mmol), 2-*n*-butyliodobenzene (187 mg, 0.72 mmol), norbornene (17 mg, 0.18 mmol), and diphenylacetylene (64 mg, 0.36 mmol) is stirred in DMF (4 mL) at 105 °C for 24 h under N$_2$. A 5% solution of H$_2$SO$_4$ is added, and the organic part is extracted with CH$_2$Cl$_2$ and dried over anhydrous Na$_2$SO$_4$. Quantitative GC analysis of the crude using an SE 30 column shows that compounds **9**[2c] and **10** (R = *n*-Bu) are present in 3% and 6%, respectively. Flash chromatography on silica with hexane as the eluent affords pure 1,5-di-*n*-butyl-9,10-diphenylphenanthrene **2** (R = *n*-Bu, 134 mg) in 84% yield as a white solid (mp 79−80 °C).

(6) Tetrabutylammonium chloride and lithium chloride were found by Larock[4b] to be very effective in the annulation reaction of *o*-iodobiphenyl with diphenylacetylene.

As shown in Table 1 the yield is strongly influenced by the *ortho* substituent R. Aryl iodides with both primary and secondary *ortho* alkyl groups give good to excellent results, while the presence of a *tert*-butyl substituent prevents the formation of the corresponding phenanthrene derivative (run 6). The reaction becomes less efficient when R is a methoxy or methoxymethylene group (runs 7 and 8) and leads to poor result when R = CO$_2$Me (run 9).

The reaction appears to be general for diphenylacetylenes and alkylphenylacetylenes. In the latter case, however, the expected phenanthrenes are formed together with allene **3** (run 12). So far no significant result has been obtained with disubstituted acetylenes containing bulky substituents. Dialkylacetylenes do not give phenanthrenes but only allenes **4** (run 13).[7] Scheme 2 reports the proposed mechanism.[2,8]

Scheme 2
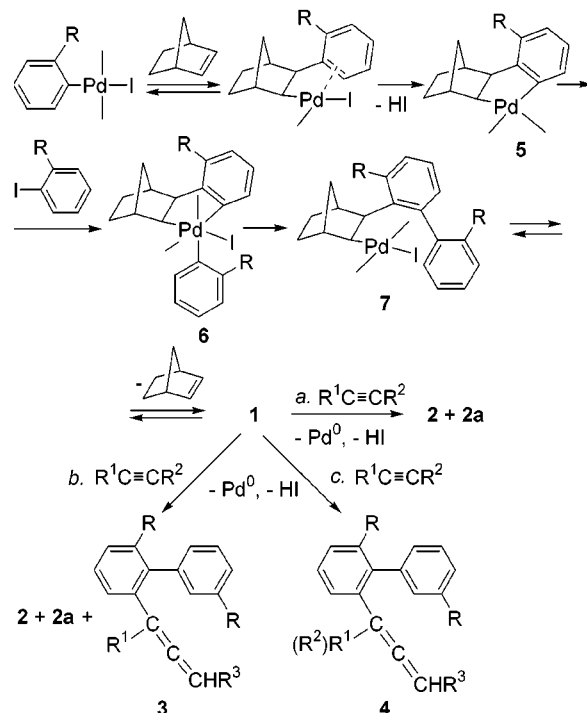
a. R^1, R^2 = phenyl, substituted phenyl
b. R^1 = phenyl, substituted phenyl; R^2 = alkyl; R^3 = H, alkyl
c. R^1, R^2 = alkyl; R^3 = H, alkyl

Oxidative addition of an *ortho*-substituted aryl iodide to palladium(0) followed by norbornene insertion and cyclization leads to arylnorbornylpalladacycle **5**. At this point a second molecule of aryl iodide reacts with palladacycle **5**, probably forming complex **6**,[9,10] which spontaneously evolves toward reductive elimination products resulting from selective coupling of the palladium-bonded aryl groups to form complex **7**. As a consequence of the presence of two *ortho* substituents, norbornene is expelled,[2,8] and the complex **1**

(7) Spectroscopic data (IR, ^{1}H and ^{13}C NMR) are in agreement with structures **3** and **4**.

(8) Catellani, M.; Motti, E. *New J. Chem.* **1998**, 759.

thus formed reacts with a diphenylacetylene derivative to give **2** or **2a** (path *a*). If an alkylphenylacetylene containing at least one hydrogen adjacent to the triple bond is used, an allenic product (**3**, isomeric mixture; path *b*) is formed as a result of β-H elimination, in addition to **2** and **2a**. With dialkylacetylenes, allenes **4** (path *c*) are obtained exclusively.

The formation of the allenic compounds **3** and **4** throws light on the mechanism insofar as the allenic to aromatic carbon bond reveals the position of the Pd−C bond into which the triple bond insertion occurs (complex **1**), thus confirming the previous steps shown in Scheme 2.

The lower yield observed by replacing an alkyl substituent with a methoxy or a methoxymethylene group is probably due to the ability of the latter to coordinate to the palladium center, thus causing a reactivity change.

Only aryl iodides bearing an *ortho* substituent react according to Scheme 2. In fact, if R = H, selective migration of the aryl group to the norbornyl site of the palladacycle occurs, followed by cyclization to afford **8** (Scheme 3).[11]
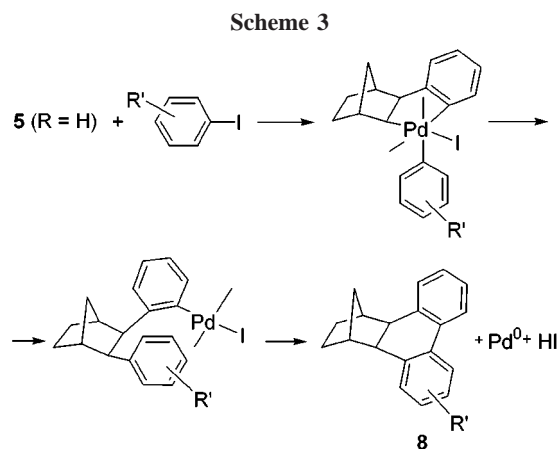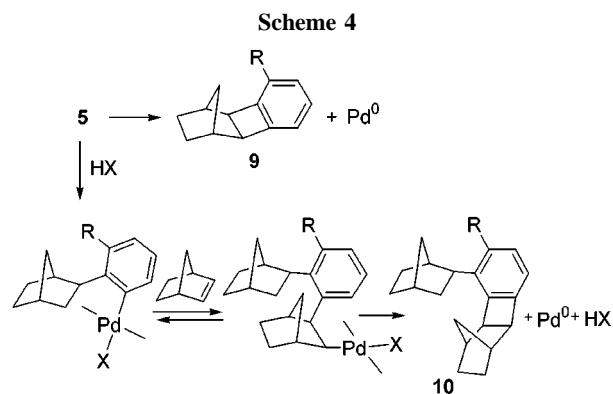
Scheme 3

Byproducts **9** and **10** containing norbornene were usually found in small amounts (2−7%). As depicted in Scheme 4, both compounds result from palladacycle **5** owing to the steric effect of the *ortho* substituent.[12,13] Compound **9** is the main product with R = *t*-Bu. Its extensive formation is likely

Scheme 4

due to both the destabilizing effect of the sterically demanding *tert*-butyl group on metallacycle **5** (R = *t*-Bu) and to the reluctance of 2-*t*-BuC$_6$H$_4$I to undergo oxidative addition to the same palladium(II) metallacycle (Scheme 2).

When R = Me, small amounts (ca. 5%) of two additional byproducts were obtained, which derive from activation of a benzylic C−H bond, as previously reported.[14]

It was ascertained that with R = *n*-Bu 1,5-disubstituted phenanthrenes did not form in the absence of norbornene, thus confirming the key role played by the strained olefin. This is a further evidence that the present procedure for the synthesis of a new class of selectively substituted phenanthrenes is quite different from the palladium-catalyzed cyclization reactions of diphenylacetylenes with aryl iodides that were studied previously,[4] in particular those described by Heck,[4a] Larock,[4b] and Dyker.[4c,d] In our case indeed the biphenylyl structure **1** is first constructed on palladium with the help of norbornene, followed by reaction with the triple bond to close the phenanthrene ring.

The reaction efficiency could also be improved, although a complete optimization study was not carried out. With R = *i*-Pr and a 200:1 molar ratio between aryl iodide and palladium acetate, compound **2** (R = *i*-Pr) was isolated in 85% yield after 24 h. With higher molar ratio the reaction selectivity still was good, but longer reaction times were required. Interestingly, with R = primary alkyl group and a 200:1 molar ratio the reaction became sluggish and long reaction times were needed, thus pointing to the requirement for an *o*-alkyl group of moderate bulkiness such as the *i*-propyl for a higher efficiency.

In conclusion, we have achieved a new synthesis of selectively disubstituted phenanthrenes by taking advantage of the effect of *o*-substituents on the reactivity of norbornene-derived palladacycle intermediates.

(9) For palladium(IV) chemistry, see: (a) Canty, A. J. *Acc. Chem. Res.* **1992**, *25*, 83 and references therein. (b) Markies, B. A.; Canty, A. J.; Janssen, M. D.; Spek, A. L.; Boersma, J.; van Koten, G. *Recl. Trav. Chim. Pays-Bas* **1991**, *110*, 477. (c) de Graaf, W.; Boersma, J.; Smeets, W. J. J.; Spek, A. L.; van Koten, G. *Organometallics* **1989**, *8*, 2907. (d) Catellani, M.; Mann, B. E. *J. Organomet. Chem.* **1990**, *390*, 251. (e) van Asselt, R.; Rijnberg, E.; Elsevier, C. *Organometallics* **1994**, *13*, 706. (f) Brunel, J. M.; Hirlemann, M.-H.; Heumann, A.; Buono, G. *J. Chem. Soc., Chem. Commun.* **2000**, 1869.

(10) On the basis of the analogy with alkylation of complex **5**, which led to isolation of palladium(IV) complexes,[9d] and the recent report of arylpalladium(IV) complexes deriving from aryl iodide addition to a palladium(II) species,[9f] we assume that also in the present case an oxidative addition of the *ortho*-substituted aryl iodide to **5** takes place affording the palladium(IV) complex **6** (which in solution may dissociate the iodide ion[9c]).

(11) (a) Catellani, M.; Chiusoli, G. P.; Castagnoli, C. *J. Organomet. Chem.* **1991**, *407*, C30. (b) Albrecht, K.; Reiser, O.; Weber, M.; Knieriem, B.; de Meijere, A. *Tetrahedron* **1994**, *50*, 383.

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Supporting Information Available: Spectroscopic data for phenanthrene derivatives (Table 1). This material is available free of charge via the Internet at http://pubs.acs.org.

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