

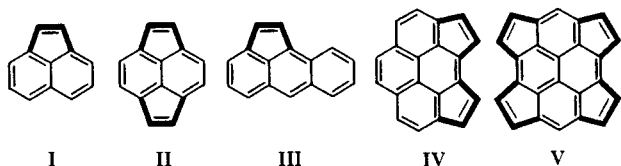
Palladium-Catalyzed Formation of Aceanthrylenes: A Simple Method for Peri-Cyclopentenelation of Aromatic Compounds

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Many efforts have been directed toward the synthesis of polynuclear aromatic hydrocarbons (PAH) that have peri-fused five- and six-membered-ring carbon fragments corresponding to portions of the fullerene surface.¹ These include polycyclic aromatic systems with potentially interesting fullerene-like photo-physical properties such as acenaphthalene (**I**), pyracylene (**II**), aceanthrylene (**III**), and several cyclopentapyrenes (e.g., **IV** and **V**). Previously reported syntheses to construct the two carbon etheno bridges highlighted in the examples involve multistep processes² or flash vacuum pyrolysis (FVP);³ the latter often results in relatively low yields. In this communication, we report a novel transformation that may ultimately lead to the facile synthesis of these PAH's.



We describe here the first example of the preparation of 2-substituted aceanthrylenes **2** via a one-step Pd(0)-catalyzed coupling of 9-bromoanthracene (**1**) with monosubstituted acetylenes (Scheme 1). While preparing 9-ethynylantracenes **3** using Sonogashira reaction conditions,⁴ we discovered that Pd(0)-catalyzed coupling of 9-bromoanthracene (**1**) with 2-methyl-3-butyn-2-ol formed 9-alkynylantracene (**3a**, R = -C(CH₃)₂OH) (Scheme 1 and Table 1) and the unexpected 2-(1-hydroxy-1-methylethyl)aceanthrylene (**2a**) (R = -C(CH₃)₂OH) in 71% purified overall yield, with a 72:28 ratio.^{5,6} Compound **3a** is pale yellow (λ_{max} at 347, 364, 383, and 405 nm) and highly fluorescent. In contrast, aceanthrylene **2a** is a reddish-orange material with no detectable fluorescence emission. Compound **2a** is highly crystalline and gives large ruby-red prisms by slow evaporation from a mixture of ethyl acetate and hexanes. The molecular

Scheme 1

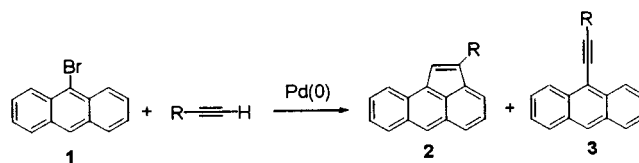


Table 1. Palladium-Catalyzed Reaction of **1** with Terminal Alkynes^a

entry	alkyne (R)	bp of alkyne (°C)	rxn conds	total yield (%) ^b	2 (%) ^c	3 (%) ^c
a	-C(CH ₃) ₂ OH	104	reflux	80–90	91	9 ⁹
b	-C(CH ₃) ₂ OH		sealed tube ^d	50	96	4
c	-C ₆ H ₅	143	reflux	62	0	100 ¹²
d	-Si(CH ₃) ₃	53	reflux	18	84	16 ¹³
e	-Si(CH ₃) ₃		sealed tube ^d	75	93	7
f	-Si(CH ₂ CH ₃) ₃	136	reflux	76	38	62
g	-Si(CH(CH ₃) ₂) ₃	51	reflux	16	37	63
h	-Si(CH(CH ₃) ₂) ₃		sealed tube ^d	67	42	58

^a Conditions: PdCl₂(PPh₃)₂ (4.5 mol %), PPh₃ (23 mol %), CuSO₄/Al₂O₃ (17 mol %), alkyne (400 mol %), Et₃N (400 mol %), benzene (deoxygenated), refluxed 16 h. ^b Total isolated yield of **2** and **3** after chromatography. ^c Relative ratios determined by ¹H NMR. ^d Sealed tube reactions were carried out at 110 °C with no copper.

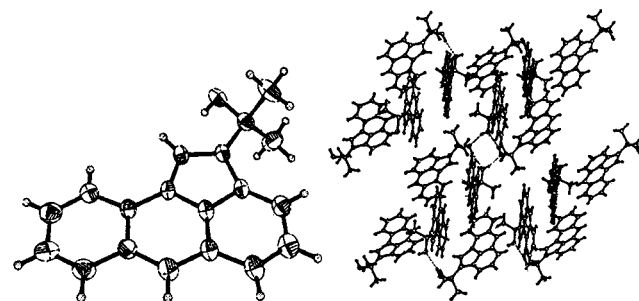


Figure 1. X-ray crystal structure of **2a** (ORTEP diagram, left). The packing view shows four aceanthrylene molecules hydrogen bonding in the crystal lattice (right).

structure of **2a** was determined and characterized by ¹H and ¹³C NMR and further confirmed by X-ray analysis.⁷ The ORTEP diagram (Figure 1, left) of aceanthrylene **2a** shows a planar nonalternant aceanthrylene core.⁸ The crystal packing (Figure 1, right) reveals a hydrogen-bonding network of four aceanthrylene molecules in a cyclic array, with two crystallographically independent molecules in the asymmetric unit cell.

The reaction was originally carried out in refluxing deoxygenated benzene in the presence of 4.5 mol % of PdCl₂(PPh₃)₂, 23 mol % of PPh₃, 17 mol % of CuI, 2 equiv of Et₃N, and 1.1 equiv of the alkyne.^{4a} We were surprised and delighted to discover the formation of aceanthrylene **2a** and we decided to explore the conditions to improve its selectivity. We first found that the yields of reaction were dependent on the amount of base used. When triethylamine was omitted, no reaction was observed and starting material **1** was recovered. Increasing the amount of base up to

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(7) **2a**: C₁₉H₁₆O, MW = 260.32, monoclinic, space group *P2₁/c*, *a* = 12.2402(13) Å, *b* = 12.6193(13) Å, *c* = 18.4528(18) Å, β = 102.93(3)°, *V* = 2777.9(5) Å³, *Z* = 4, ρ_{calcd} = 1.245 Mg/m³, *F*(000) = 1104, λ = 0.7173 Å, μ (Mo K α) = 0.075 mm⁻¹, *T* = 20 °C, crystal size = 0.3 × 0.2 × 0.2 mm³. Of the 17847 reflections collected (1.71 ≤ 2 θ ≤ 28.31°), 6631 [*R*(int) = 0.0560] were independent reflections; max/min residual electron density 132 and -129 e nm⁻³, *R*1 = 0.0389 (*I* > 2 σ (*I*)) and *wR*2 = 0.0607.

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10 equiv gave better yields of **2a** and **3a**, while the relative ratios of the two isomers remained unchanged. When triethylamine was used as the solvent in a sealed tube, the reaction gave mostly **3a** and small amounts of **2a**. The results were consistent with a recent report by Crisp and Jiang,⁹ in which they obtained the straight coupling product **3a** in the presence of Pd(PPh₃)₄, PPh₃, CuBr, and LiBr, with piperidine as the solvent. Originally, we speculated that the formation of **2** might first involve the formation of **3** and subsequent palladium-catalyzed intramolecular insertion of the alkyne into anthracene to form **2**. However, no formation of **2** was observed when **3** was subjected to the same Pd(0)-catalyzed reaction conditions.

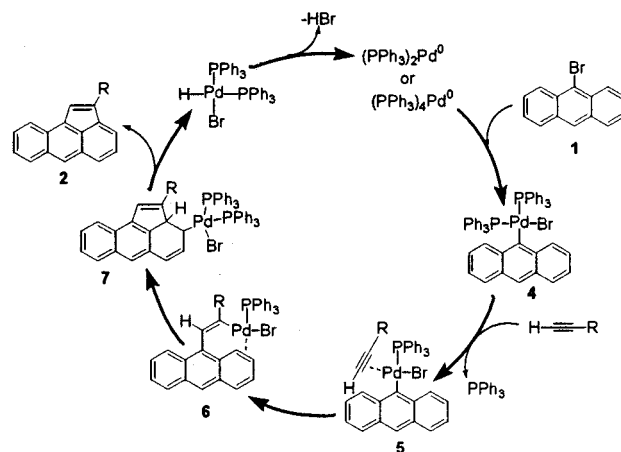
Keeping the molar ratio of PPh₃:Pd:Cu at 5.3:1:3.7,^{4a} we carried out a series of optimization experiments on the reaction of **1** with 2-methyl-3-butyne-2-ol. We explored the replacement of CuI with alumina-supported CuSO₄ and the results were extremely promising. It is well-known that CuI activates terminal alkynes to form a copper acetylide,¹⁰ which undergoes transmetalation with arylpalladium halide to form the alkynylpalladium species and upon reductive elimination gives the final product **3a**. When copper was omitted from the reaction mixture, we obtained a 96:4 mixture of **2a** and **3a** in very low yields. The total yield of **2a** and **3a** significantly increased to 80–90% with a 91:9 ratio when 4 equiv of Et₃N, 4 equiv of alkyne, and alumina-supported CuSO₄¹¹ were used (Table 1, entry **a**).

Encouraged by this result, we tested the reaction conditions with other terminal acetylenes, including silane derivatives with the hope of obtaining the parent cyclopenta-fused aromatic hydrocarbon after deprotection (Table 1, entry **d–h**). Trimethylsilyl (TMS) acetylene (entry **d**) gave a comparable ratio of **2** to **3** (84:16) with an overall yield of 18%. The total yield increased to 76% with a ratio of 38:62 in favor of the straight coupling product **3** when triethylsilyl (TES) acetylene was used (entry **f**). Palladium-catalyzed coupling of **1** with triisopropylsilyl (TIPS) acetylene (entry **g**) gave the lowest total conversion (16%) with a 37:63 mixture of **2** to **3**.

The results in Table 1 can be understood in terms of the boiling point and steric bulk of the alkynes. In the case of TMS acetylene and TIPS acetylene, which have boiling points of 53 and 51 °C, respectively, the overall conversion was significantly reduced. The yield of **2** decreased drastically in favor of **3** when bulky TIPS acetylene (entry **g**) was used. Coupling with phenyl acetylene (entry **c**) gave 100% of **3** with a 62% conversion.

It was evident that under reflux conditions lower boiling acetylenes produced lower overall yields than acetylenes with higher boiling points (entry **a, c, f** versus **d, g**). When 9-bromoanthracene (**1**) and TMS acetylene were reacted in a sealed pressure tube at 110 °C, under the same conditions with CuSO₄/Al₂O₃ as outlined in Table 1, all the starting material had reacted after 16 h to give isolated yields greater than 90% of **2d** and **3d** with a 87:13 ratio. The total yield and product ratios increased in favor of **2**, even in the absence of copper (entries **b, e, h**). Coupling of **1** with TMS acetylene gave 75% isolated yield with a 93:7 ratio (entry **e**).¹⁴ Coupling of **1** with TIPS acetylene under

Scheme 2. Proposed Mechanism for the Palladium-Catalyzed Formation of Aceanthrylene **2**



similar conditions also gave higher total isolated yield (67%) and a 42:58 ratio of **2e**:**3e** (entry **h**). These results support the notion that the role of copper is to activate the terminal alkyne to form ethynyl anthracene **3**. When copper was omitted, a slight increase of **2** was observed in both the TMS and TIPS acetylenes. Unlike experiments run in sealed pressure tubes at 110 °C, experiments run under refluxing conditions in the absence of copper gave high selectivity, but lower chemical yields of **2** (Table 1).

A plausible mechanism for this unprecedented palladium-mediated intramolecular aryl halide–alkyne transformation is shown in Scheme 2. Oxidative addition of **1** to Pd(0) generates species **4**, which, in the presence of a terminal alkyne and in the absence of copper, coordinates through interaction with the triple bond (π - or side bound) to give intermediate **5**. Insertion into the alkyne forms a thermally stable alkenylpalladium intermediate¹⁰ **6**, which is capable of undergoing further intramolecular alkene insertion into the double bond of anthracene to generate the cyclized intermediate **7**. Rearomatization of intermediate **7**, perhaps in a stepwise fashion, generates aceanthrylene **2** and HPdBr(PPh₃)₂, which reduces back to Pd(0) species for catalytic recycling. A similar reaction mechanism was proposed in the palladium-catalyzed intermolecular-controlled insertion of benzyne with alkenes and alkynes.¹⁵

We are currently investigating the scope of this palladium-catalyzed transformation with other aryl bromides and the preliminary results obtained thus far are extremely promising. To fully understand the factors determining the selectivity, we are also examining the mechanism in detail. This novel palladium-catalyzed transformation provides a versatile new synthetic method for the synthesis of strained cyclopenta-fused aromatic hydrocarbons.

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Supporting Information Available: Experimental procedures and spectroscopic data for **2a**, **2d**, **2f–g**, **3a**, **3c–d**, and **3f–g**; stereoscopic views and X-ray tables for **2a** (PDF). This material is available free of charge via the Internet at <http://pubs.acs.org>.

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(14) Sealed tube conditions: 4.5 mol % PdCl₂(PPh₃)₂, 23 mol % PPh₃, 400 mol % Et₃N, 400 mol % alkyne, benzene (deoxygenated), 110 °C, 16–24 h.

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