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# Synthesis of polynuclear aromatic compounds through net [5+5]-cycloaddition of 2-alkynylarylcarbene complexes and enyne–aldehyde derivatives

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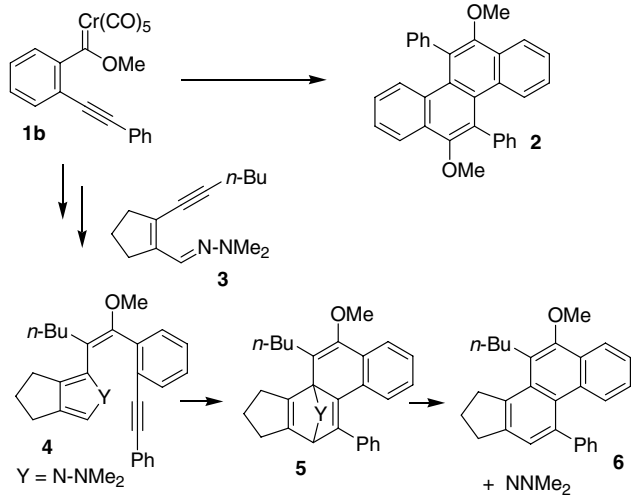
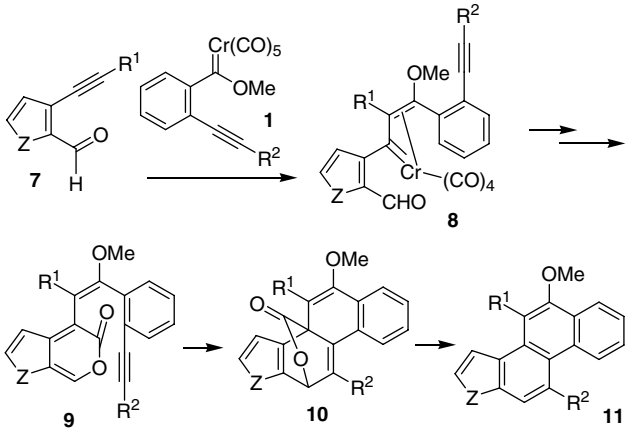
**Abstract**—Coupling of *o*-alkynylphenylcarbene complexes and –*o*-alkynylheteroarene carboxaldehydes leads to heterocycle annulated phenanthrene derivatives.


Polynuclear aromatic compounds are considered to be important synthetic targets due to the efforts made to understand their roles in carcinogenesis and as potential building blocks for fullerenes and nanotubes.[1] A few isolated reports have demonstrated the potential of alkynylphenylcarbene complexes (e.g., **1b**, Scheme 1) in the construction of polynuclear aromatic compounds. Thermal decomposition results in the rapid one-step assembly of chrysene derivatives (e.g., **2**) in a net dimerization process.[2] Alkynylphenyl carbene complexes can also couple with enyne hydrazones (e.g., **3**) to afford phenanthrenes in a complex tandem reaction[3] employing intramolecular alkyne–aminopyrrole Diels–Alder reaction and nitrene expulsion[4] for the construction of two new aromatic rings. Unrelated processes not involving intermolecular alkyne coupling were also reported for 2-alkynylphenylcarbene complexes.[5] In this letter, coupling of 3-alkynyl-2-formylheteroaromatic systems (e.g., **7**, Z = O or S, Scheme 2) with alkyne–carbene complexes will be discussed. Previous studies have shown




**Scheme 1.**




**Scheme 2.**

*Keywords*: Carbene complexes; Alkynes; Pyrones; Diels–Alder reaction; Polynuclear aromatics.
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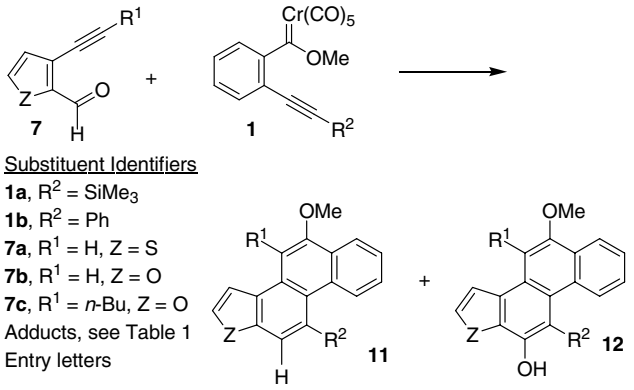
**Table 1.** Synthesis of annulated phenanthrenes through coupling of alkynylphenylcarbene complexes and alkynylheteroarene–carboxaldehydes




| Entry[a] | Z | $R^1$ | $R^2$ | Yield (%) **11** | Yield (%) **12** |
|---|---|---|---|---|---|
| A[b,c] | S | H | TMS | 21[d] | 63[d] |
| B[b,e] | O | H | TMS | 56[d] | 6[d] |
| C | S | H | Ph | 57 | 9 |
| D | O | H | Ph | 60 | 0 |
| E | O | *n*-Bu | Ph | 88 | 0 |

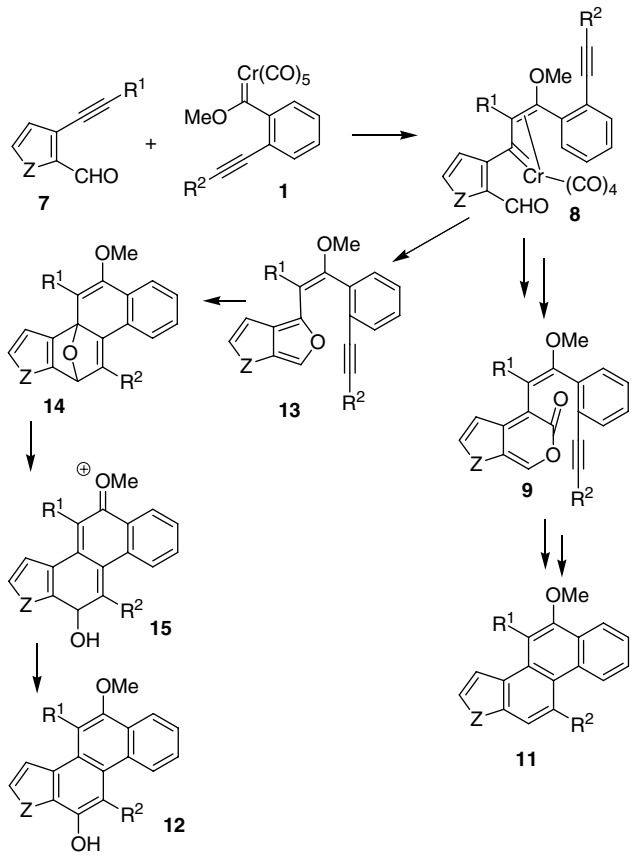
[a] Entry letters correspond to substituent identifiers for compounds **8**–**15**.
[b] The crude reaction mixture was treated with $Bu_4NF$ prior to isolation.
[c] For a detailed procedure, see Ref. 13.
[d] $R^2 = H$ in the final products **11** and **12**.
[e] For a detailed procedure, see Ref. 14.

that these alkynes afford furano[3,2-*c*]pyran-4-ones and thieno[3,2-*c*]pyran-4-ones (e.g., intermediate **9**) upon coupling with carbene complexes.[6] The predicted annulated phenanthrene synthesis in Scheme 2 employs the more conventional Diels–Alder based cycloaromatization of pyrones and alkynes as a key step.[7] Both of the reacting partners, alkynylphenylcarbene complexes (**1**)[8] and alkynylheterocyclic carboxaldehydes (**7**),[9] are readily available compound classes.

Initial investigations involved terminal alkynes in the heterocyclic partner to minimize possible competitive formation of the dimeric compound **2** of Scheme 1.[10] The initial reaction tested was the coupling of silylalkyne phenylcarbene complex **1a** and the thiophene derivative **7a** featuring a terminal alkyne (Table 1, entry A). Although the overall process was quite efficient, two products were obtained from this reaction: the expected (minor) product, phenanthro[2,1-*b*]thiophene derivative **11a**, and the corresponding phenolic product **12a**. Since the crude reaction mixture revealed mixtures of silylated and desilylated compounds, the crude reaction mixture was treated with fluoride ion to effect complete desilylation and thus simplify the isolation. None of the thermal dimerization product analogous to **2** were observed in this reaction. A similar reaction applied to the furan analog resulted in primarily the nonphenolic product **11b** (entry B). Similar results were obtained for phenylethynylphenylcarbene analogs (entries C and D). In these cases, only very minor amounts of phenolic byproducts were observed. The butylated acetylene analog **7c** entered into the most efficient coupling reaction (entry E), providing the desired product **11e** in high yield as the exclusive reaction product. This result is surprising in that both alkynes feature the same degree of substitution, yet there is complete selectivity for heterocoupling leading to **11e** over homocoupling leading to dimerization product **2**.

The desired products **11** are the result of the anticipated reaction pathway depicted in Scheme 2. The phenolic byproducts can arise via the alternative reaction pathway depicted in Scheme 3. The critical divergent step is direct closure of intermediate vinylcarbene complex **8** to the furan **13** instead of closure after CO insertion to form pyrone **9**. After the intramolecular Diels–Alder reaction to form oxanorbornadiene **14**, acid-catalyzed reaction can lead to phenol **12**. Previous studies showed that the furan-forming pathway is more prevalent when the initial ring is thiophene instead of furan,[6] which is also noted in the results in Table 1 (Compare entry A with entry B and entry C with entry D). This effect can likely be attributed to the greater ring strain (see Fig. 1) in furo[3,4-*b*]furan (**16**) compared with thieno[2,3-*c*]furan (**17**).[11] Both of these ring systems and pyrrole ring analogs have precedent.[12]

The final step of the formation of phenanthrenols **12** involves acid-catalyzed rearrangement of oxanorbornene **14** to **12**. Numerous examples of acid-catalyzed conversion of benzo-oxanorbornenes to naphthalenes have been reported.[15] Although no acid was deliberately added to the reaction, this process might have occurred during chromatographic purification. The process is anticipated to be unusually facile in this system, since intermediate carbocations (e.g., **15**) are stabilized by the enol ether system. Protiodesilylation was a problem during the reactions employing alkynylsilane complex **1a**. Protiodesilylation was noted in other reactions transforming arene oxides to phenols.[16] Desilylation is



Scheme 3.

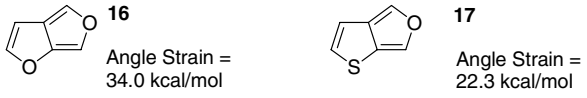
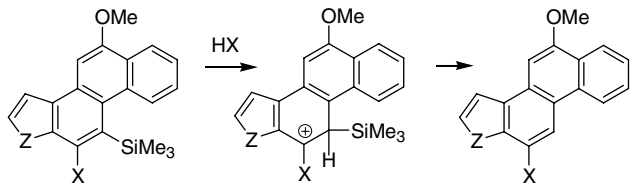


Figure 1. Comparison of angle strain in furan-fused heterocycles (MM2).

anticipated to be especially fast in this system owing to the stabilization of an intermediate carbocation derived from ipso protonation by the adjacent furan/thiophene ring system (Scheme 4),[17] and should be even more facile in the phenolic compounds where X is OH.

A somewhat curious observation is the greater prevalence of phenolic compounds resulting from silylalkynyl arylcarbene complexes compared with phenylalkynyl arylcarbene complexes (compare entry A with entry C and entry B with entry D). The origin of this effect is unclear. According to the proposed mechanism, this alkyne is somewhat remote to the reaction site until the Diels–Alder step of the reaction. If formation of the furans was a reversible process, then the product ratios may simply reflect the efficiency of capture of the furanothiophene intermediate.



Scheme 4.

In summary, we have shown that alkynylphenylcarbene complexes (**1**) can couple with alkynylheteroaromatic carboxaldehydes (**7**) to afford heterocycle-annulated phenanthrenes (**11** and **12**). Both simple phenanthrenes (**11**) and the analogous phenolic compounds **12** were observed in this reaction. The product distributions were attributed to the involvement of either a pyrone intermediate for eventual formation of phenanthrene **11** or a furan intermediate for eventual formation of phenanthrenol **12**.

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7. For a review of pyrone Diels–Alder reactions, see: (a) Afarinkia, K.; Vinader, V.; Nelson, T. D.; Posner, G. H. *Tetrahedron* **1992**, *48*, 9111–9171; For a more recent review, see: (b) Woodard, B. T.; Posner, G. H. *Adv. Cycloaddition* **1999**, *5*, 47–83.
8. These complexes were prepared from 1,2-dibromobenzene or 2-iodo-1-bromobenzene in a sequence involving Sonogashira coupling, followed by lithiation of the resulting 1-alknynyl-2-bromobenzene derivative and conversion to the carbene complex. For a detailed procedure, see Ref. 2.
9. The compounds were prepared from 2,3-dibromothiophene (or 2,3-dibromofuran) in a sequence involving selective lithiation at the 2-position and formylation using DMF, followed by Sonogashira coupling using the resulting 3-bromo-2-thiophenecarboxaldehyde derivative (or furan analog). For a detailed procedure, see Ref. 6.
10. The following papers feature examples where terminal alkynes are the initial reaction sites in carbene–dialkyne coupling reactions. (a) Wulff, W. D.; Kaesler, R. W.; Peterson, G. A.; Tang, P. C. *J. Am. Chem. Soc.* **1985**, *107*, 1060–1062; (b) Zhang, Y.; Herndon, J. W. *Tetrahedron* **2000**, *56*, 2175–2184.

11. The calculations were done at the MM2 level. This is a relatively low level of theory, however, this method provides the most direct measure for the parameter angle strain.
12. For furo[2,3-*b*]furan derivatives, see: (a) Eberbach, W.; Laber, N.; Bussinius, J.; Fritz, H.; Ribs, G. *Chem. Ber.* **1993**, *126*, 975–995; For thieno[2,3-*c*]furan derivatives, see: (b) Schoening, A.; Debaerdemaeker, T.; Zander, M.; Friedrichsen, W. *Chem. Ber.* **1989**, *122*, 1119–1131.
13. A solution of carbene complex **1a** (122 mg, 0.30 mmol) in THF (12 mL) was added dropwise to a refluxing solution of alkyne–aldehyde **7a** (41 mg, 0.30 mmol) in THF (15 mL) and kept at reflux for 18 h. The resulting reaction mixture was concentrated on a rotary evaporator. To the residue were added silica gel (1 g) and chloroform (20 mL), and the mixture was stirred in the air for 10 h, and then filtered and concentrated on a rotary evaporator. The residue was dissolved in THF (10 mL), and tetrabutylammonium fluoride (2 mL of 1 M THF solution) was added. The reaction mixture was stirred for 20 h at room temperature. The reaction was concentrated on a rotary evaporator and the residue was purified by flash chromatography on silica gel using first (9:1) hexane as eluent. The product in the first fraction was identified as **11a** (17 mg, 21% yield). $^1$H NMR: $\delta$ 8.71 (dd, 1H, $J = 8.6$, 1.5 Hz), 8.53 (d, 1H, $J = 9.2$ Hz), 8.41 (m, 1H), 7.96 (dd, 1H, $J = 2.2$, 0.7 Hz), 7.92 (dd, 1H, $J = 5.4$, 0.7 Hz), 7.74–7.56 (m, 2H), 7.57 (d, 1H, $J = 5.4$ Hz), 7.50 (s, 1H), 4.15 (s, 3H); $^{13}$C NMR($CDCl_3$): $\delta$ 154.3, 138.3, 136.0, 131.7, 128.4, 127.3, 125.8, 125.7, 125.5, 122.8, 122.6, 122.5, 121.9, 119.4, 118.4, 98.6, 55.5. Mass Spec (EI): *m*/*z* 264 ($M^+$, 78), 249 (30), 221 (100), 207 (19); HRMS: calcd for $C_{17}H_{12}OS$ 264.06089, found 264.06153. The product in the second fraction was identified as phenolic compound **12a** (53 mg, 63% yield). $^1$H NMR (acetone-$d_6$): $\delta$ 9.62 (br s, 1H), 8.74 (dd, 1H, $J = 8.8$, 1.8 Hz), 8.49 (dd, 1H, $J = 8.8$, 1.8 Hz), 8.33 (d, 1H, $J = 5.5$ Hz), 8.18 (s, 1H), 7.92 (d, 1H, $J = 5.5$ Hz), 7.88 (s, 1H), 7.81 (ddd, 1H, $J = 8.8$, 7.0, 1.8 Hz), 7.73 (ddd, 1H, $J = 8.8$, 7.0, 1.8 Hz), 4.30 (s, 3H); $^{13}$C NMR (acetone-$d_6$): 153.3, 150.5, 139.7, 132.2, 130.4, 128.1, 127.6, 127.3, 127.0, 126.0, 124.3, 124.2, 124.0, 123.7, 102.6, 100.5, 56.4. Mass Spec (EI): *m*/*z* 280 ($M^+$, 100), 265 (26), 248 (7), 237 (17), 208 (9); HRMS: calcd for $C_{17}H_{12}O_2S$ 280.05580, found 280.05465.
14. The above procedure was employed using carbene complex **1a** (122 mg, 0.30 mmol) and furanaldehyde **7b** (36 mg, 0.30 mmol). A white solid identified as nonphenolic phenanthrene **11b** was obtained (42 mg, 56% yield). $^1$H NMR ($CDCl_3$): $\delta$ 8.66 (d, 1H, $J = 8.1$ Hz), 8.52 (d, 1H, $J = 8.8$ Hz), 8.42 (dd, 1H, $J = 8.1$, 1.5 Hz), 7.78 (d, 1H, $J = 2.2$ Hz), 7.74–7.57 (m, 3H), 7.26 (m, 2H). $^{13}$C NMR ($CDCl_3$): $\delta$ 154.3, 153.5, 144.1, 131.9, 127.3, 126.9, 125.5, 125.4, 123.2, 122.6, 121.7, 119.5, 109.0, 105.3, 98.3, 55.4; Mass Spec (EI): *m*/*z* 248 ($M^+$, 90), 233 (18), 205 (100), 176 (39); HRMS: calcd for $C_{17}H_{12}O_2$ 248.08373, found 248.08359.
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