Flexible Synthesis of Phenanthrenes by a PtCl₂-Catalyzed Cycloisomerization Reaction

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Received May 23, 2002

Abstract: Readily available biphenyl derivatives containing an alkyne unit at one of their ortho positions are converted into substituted phenanthrenes upon exposure to catalytic amounts of either PtCl₂, AuCl₃, GaCl₃, or InCl₃ in toluene. This 6-endo-dig cyclization likely proceeds through initial π-coordination of the alkyne unit followed by interception of the resulting π-metal complex by the adjacent aren ring. The reaction is inherently modular, allowing for substantial structural variations and for the incorporation of substituents at any site of the phenanthrene product except C-9. Moreover, the reaction is readily applied to the heterocyclic series as exemplified by the preparation of benzoindoles, naphthothiophenes as well as bridgehead nitrogen heterocycles.

Since the pioneering studies of Murai et al.,¹ PtCl₂ is rapidly gaining importance as a convenient catalyst for a host of skeletal rearrangements of enynes and related substrates.²-⁸ Although the transformations are seemingly quite diverse in nature, substantial evidence has accumulated that they are invariably triggered by π-complexation of the alkyne to the transition metal, rendering the alkyne susceptible to attack by an external or a tethered nucleophile.⁹ In pursuit of our previous investigations in this field,¹⁰ we now report a flexible synthesis of phenanthrenes based on a PtCl₂-catalyzed carbocyclization reaction of alkylnylated biphenyl derivatives.¹¹-¹³

The required substrates 2 are prepared in two steps as shown in Scheme 1.¹⁴ Standard Suzuki cross-coupling reactions¹⁵ employing either 2-bromobenzaldehyde (path A) or 2-formyl-benzeneboronic acid (path B) afford sub-

![Scheme 1](image)

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stituted biphenyl aldehyde derivatives 1, which are converted into the required alkyynes 2 according to the Corey–Fuchs protocol \(^{(18)}\) or in one step by reaction with lithio trimethylsilyl diazomethane. \(^{(17)}\) Addition of an electrophilic metal salt or metal complex leads to an equilibrium between the alkyne 2 and the corresponding γ\(^2\)-complex; if the latter is intercepted by the adjacent aromatic ring, a C–C bond formation with concomitant release of the catalyst will ensue. Screening of a set of different metal species has shown that either PtCl\(_2\) or AuCl\(_3\) \(^{(18)}\) in toluene at 80 °C not only release of the catalyst will ensue. aromatic ring, a C
\(\text{Me} \quad \text{H} \quad \text{PtCl}_2 \quad \text{toluene, 80 °C, 22 h} \quad 100 \quad 96:4 \quad 53\)
\(\text{C} \quad \text{Me} \quad \text{H} \quad \text{PtCl}_2 \quad \text{toluene, 80 °C, 22 h} \quad 100 \quad 44:56 \quad 44\)
\(\text{AuCl}_3 \quad \text{toluene, 80 °C, 22 h} \quad 100 \quad 97:3 \quad 95\)
\(\text{PtCl}_2 \quad \text{toluene, 80 °C, 16 h} \quad 100 \quad 95:5 \quad 76\)
\(\text{PtCl}_2(\text{PhCN})_2/2\text{AgBF}_4 \quad \text{CH}_2\text{Cl}_2, \text{rt}, 4 h \quad 100 \quad 87:13 \quad 56\)
\(\text{RhCl}_3, \text{RuCl}_3, \text{c} \quad \text{toluene, 80 °C, 22 h} \quad 100 \quad 92:8 \quad 82\)
\(\text{PtCl}_2(\text{PhCN})_2/2\text{NH}_4\text{PF}_6 \quad \text{CH}_2\text{Cl}_2, \text{rt}, 4 h \quad 100 \quad 90:10 \quad 82\)
\(\text{RuCl}_3 \quad \text{Me COOMe} \quad \text{PtCl}_2 \quad \text{toluene, 100 °C, 24 h} \quad 100 \quad 60:40 \quad 87^c\)

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**TABLE 1. Screening of the Activity and Selectivity of Different Catalysts in the Cycloisomerization of the Ortho-alkynylated Biphenyl Derivatives 2a–e**

| substrate | R     | X     | catalyst | conditions | GC % | yield | 3 | 4 | yield |%
|-----------|-------|-------|----------|------------|------|-------|---|---|-------|
| 2a        | OMe   | H     | PtCl\(_2\) | toluene, 80 °C, 22 h | 0    |   | 53 | | |
| 2b        | Me    | H     | PtCl\(_2\) | toluene, 80 °C, 20 h | 100 | 97:3 | 64 | | |
| 2c        | Me    | Me    | PtCl\(_2\) | toluene, 80 °C, 20 h | 100 | 100:0 | 89 | | |
| 2d        | Me    | COOMe | PtCl\(_2\) | toluene, 80 °C, 40 h | 73  | 5:95 | | | |
| 2e        | Me    | C\(_2\)H\(_4\)OMe | PtCl\(_2\) | toluene, 100 °C, 24 h | 100 | 60:40 | 87 | | |

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\(^{(20)}\) Note that this pattern is distinctly different from the one described in Murai’s reports on seemingly related PtCl\(_2\)-catalyzed dihydropyranthene syntheses, which occur via an 6-exo-dig cyclization followed by an isomerization of the exo-methylene product initially formed; ref 11a.

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**Note:** It makes clear that the observed reactions are not just thermal electrocyclizations but definitely require assistance by the metal cation.

A notable feature observed for the whole set of substrates investigated (Tables 1 and 2) is the pronounced preference for the 6-exo-dig cyclization to give phenan-threnes over the conceivable 5-exo mode. \(^{(20)}\) The only exception is compound 2d in which the strongly electron-withdrawing ester group on the alkyne not only diminishes the reaction rate but also overturns this inherent bias by enforcing a 1,4-addition process formally corresponding to the 5-exo pathway (3d; 4d = 5:95). The tolane derivative 2e gives a mixture of both possible isomers, i.e., the phenanthrene 3e and the corresponding 9-alkylidene fluorene derivative 4e, in a ~3:2 ratio.

In a formal sense, this new phenanthrene synthesis is reminiscent of the endo-selective cyclizations of dienyl...
TABLE 2. Formation of Phenanthrenes and Heterocyclic Congeners by Cyclization of Ortho-alkynylated Biaryls; All Reactions Were Carried out with 5 Mol % PtCl$_2$ in Toluene at 80 °C unless Stated Otherwise

| Entry | Substrate | t (h) | Products | Yield |
|-------|-----------|-------|----------|-------|
| 1     | ![Substrate 1](image1) | 16    | ![Product 1](image2) | 76% / 95%$^a$ |
| 2     | ![Substrate 2](image3) | 20    | ![Product 2](image4) | 73% (R = H) |
| 3     | ![Substrate 3](image5) | 20    | ![Product 3](image6) | 89% (R = Me) |
| 4     | ![Substrate 4](image7) | 20    | ![Product 4](image8) | 65% |
| 5     | ![Substrate 5](image9) | 21    | ![Product 5](image10) | 75% |
| 6     | ![Substrate 6](image11) | 17    | ![Product 6](image12) | 70% (4:1) |
| 7     | ![Substrate 7](image13) | 20    | ![Product 7](image14) | 55% |
| 8     | ![Substrate 8](image15) | 24    | ![Product 8](image16) | 94% |
| 9     | ![Substrate 9](image17) | 20    | ![Product 9](image18) | 54% |
| 10    | ![Substrate 10](image19) | 14    | ![Product 10](image20) | 63% (R = H) |
| 11    | ![Substrate 11](image21) | 20    | ![Product 11](image22) | 76% (R = Me) |
| 12    | ![Substrate 12](image23) | 30    | ![Product 12](image24) | 56% (R = H) |
| 13    | ![Substrate 13](image25) | 13    | ![Product 13](image26) | 80% (R = C$_6$H$_{13}$)$^b$ |
| 14    | ![Substrate 14](image27) | 20    | ![Product 14](image28) | 91% (R = C$_6$H$_{13}$)$^c$ |

$^a$ Using AuCl$_3$ (5 mol %) as the catalyst. $^b$ Using GaCl$_3$ (10 mol %) as the catalyst; in this case, the use of either PtCl$_2$ or AuCl$_3$ led to <40% conversion. $^c$ Using InCl$_3$ (5 mol %) in toluene at 100 °C as the catalyst.
alkynes A and related substrates catalyzed by either \([\text{cymene}(\text{PPh}_3)\text{RuCl}_2]\) or \(\text{W(CO)}_5\). These reactions likely involve vinylidene complexes B, which undergo a \(6\pi\)-electrocyclization to form the new arene ring in product C. Since only terminal alkynes can afford such intermediates via complexation followed by a 1,2-hydride shift (cf. \(A \rightarrow B\)), however, the scope of this methodology is inherently limited. The platinum-catalyzed phenanthrene synthesis, in contrast, works equally well or even better with nonterminal alkynes as evident from entries 3, 8, and 11 in Table 2, suggesting that the activation of the \(\pi\)-system by coordination to Pt(II) rather than the formation of metal vinylidenes suffices to trigger the observed ring closure.

The examples compiled in Table 2 show the generality of this novel entry into phenanthrenes. In principle, this method allows the introduction of substituents at any position except C-9. The ready reaction of compound \(R\) (easily prepared from \(A\)) illustrates that dihydrophenanthrenes are well or even better with nonterminal alkynes as evident from entries 3, 8, and 11 in Table 2, suggesting that the activation of the \(\pi\)-system by coordination to Pt(II) rather than the formation of metal vinylidenes suffices to trigger the observed ring closure.

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Acknowledgment. Generous financial support by the Deutsche Forschungsgemeinschaft (Leibniz award to A.F.) and by the Fonds der Chemischen Industrie is gratefully acknowledged. We thank the OMG AG & Co KG, Hanau, for a generous gift of noble metal salts.

Supporting Information Available: Full experimental details including procedures for the preparation of the starting materials as well as the analytical and spectroscopic data of all new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

J O025962Y

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