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Bismuth-Catalyzed Synthesis of Polycyclic Aromatic Hydrocarbons (PAHs) with a Phenanthrene Backbone via Cyclization and Aromatization of 2-(2-Arylphenyl)vinyl Ethers

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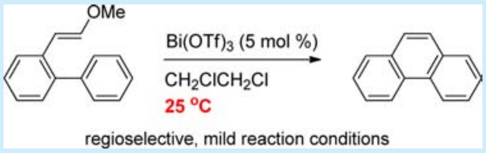
Supporting Information

ABSTRACT: The reaction of 2-(2-arylphenyl)vinyl ethers in the presence of a catalytic amount of bismuth(III) triflate gave substituted phenanthrenes in excellent yields under mild reaction conditions. The reaction was also applied to the construction of other polycyclic aromatic hydrocarbons (PAHs), such as chrysene, helicene, and pyrene having a phenanthrene backbone, via regioselective cyclization. This method has the advantages of easy availability of the cyclization precursors, operational simplicity, and high reaction efficiency.



Polycyclic aromatic hydrocarbons (PAHs) have received attention, especially in materials science, due to their utility in photoelectronic devices such as field-effect transistors, light-emitting diodes, and solar cells.[1] Most of the PAHs consist of phenanthrene molecules, which are common in biologically active compounds.[2] A variety of approaches for the construction of their backbone have been reported.[1a,3−7] While the approach using oxidative or photocyclization of stilbene derivatives is most common, the process requires electron-rich stilbenes as substrates or high-pressure photoirradiation in the presence of iodine as an oxidant and propylene oxide as an acid scavenger.[3] Thus, this approach may be limited by functional group intolerance and starting material availability. Alternative approaches include ring-closing olefin metathesis (RCM) of 2,2′-divinylbiaryls,[4] successive Friedel−Crafts acylation and Clemmensen reduction followed by the Haworth reaction,[5] and cycloisomerization of 2-ethynylbiaryls.[6] Although these methods are useful, they require high temperatures to promote the reaction or multistep sequences to obtain the phenanthrene structure, which hampers their application in the syntheses of complex target molecules. The importance of PAHs makes the development of alternative and efficient routes to suitably functionalized phenanthrene derivatives directly from simple substrates in fewer steps an important challenge.

This report describes a facile and efficient catalytic approach that involves closure of the central ring through intramolecular carbon−carbon bond formation of an *ortho*-functionalized biaryl-type precursor, readily accessible by cross-coupling chemistry. Although the cyclization of vinyl ethers to prepare phenanthrene derivatives has been reported, most of these processes require the use of an excess of strong acid promoters, which seriously limits the substrate scope.[8]

The cyclization precursor 2-(2-methoxyethenyl)biphenyl **1a** could be synthesized via the Wittig reaction of 2-phenylbenzaldehyde with (methoxymethylene)triphenylphosphorane in 84% yield as a mixture of stereoisomers (E/Z = 70/30) (Scheme 1). Treatment of vinyl ether **1a** with a catalytic amount of In(OTf)$_3$ in 1,2-dichloroethane at 25 °C for 2 h afforded the expected phenanthrene **2a** in 76% yield, along with the formation of dimer **3a** in 2% yield (Table 1, entry 1).[9] The lack of recovery of **1a** after completion of the reaction indicates that both the *E*- and *Z*-isomers of **1a** could serve as cyclization precursors. When the reaction was performed in the presence of BiCl$_3$, **2a** was the product obtained in the highest yield, although a longer reaction time was required for complete

Scheme 1. Preparation of Vinyl Ether 1a

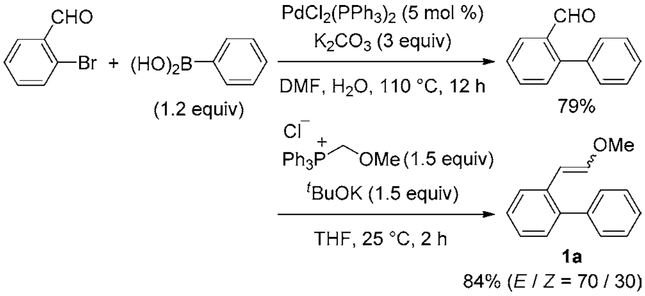


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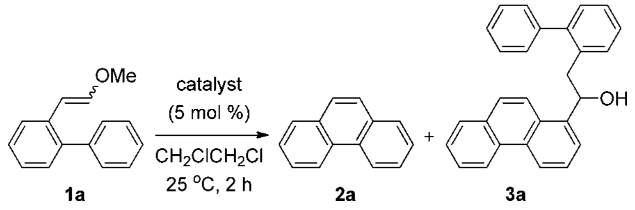
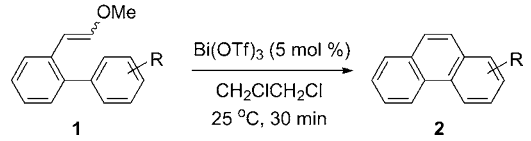
Table 1. Transition-Metal-Catalyzed Cyclization and Aromatization of Vinyl Ethers 1

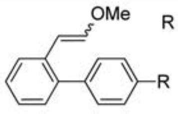
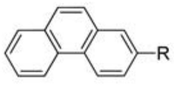
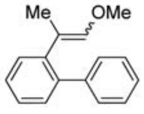
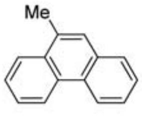
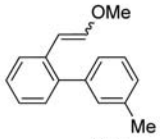
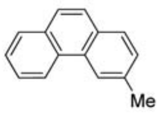
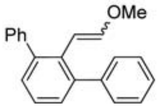
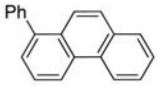


entry	catalyst	time/h	yield of **2a**^{a}/%	yield of **3a**^{a}/%
1	$In(OTf)_3$	2	76	2
2	$Bi(OTf)_3$	2	94(93)	5(4)
3	$BiCl_3$	24	99 (96)	0
4	$FeCl_3$	2	90	6
5	$PtCl_2$	2	0^b	0
6	$AuCl_3$	2	92	3

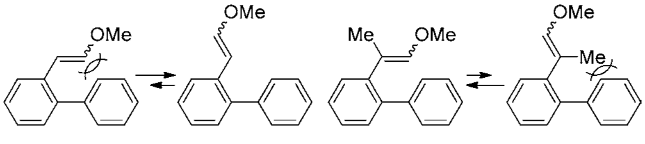
[a] Determined by ^{1}H NMR. Values in parentheses are isolated yields. [b] 99% of **1a** was recovered.

Table 2. Bismuth-Catalyzed Synthesis of Phenanthrene Derivatives 2 *via* Cyclization and Aromatization of Vinyl Ethers 1



Entry	Substrate			Product		Yield^a / %
1		R = OMe	**1b**		**2b**	91
2		Me	**1c**		**2c**	96
3^b		Cl	**1d**		**2d**	15
4^b		CF_3	**1e**		**2e**	0
5			**1f**		**2f**	95
6			**1g**		**2g**	95^c
7			**1h**		**2h**	96

[a] Isolated yields. [b] For 2h. [c] Obtained as a mixture of **2g** and 1-methylphenanthrene **2g′** in the ratio of 87:13.



1a **1f**

Figure 1. Possible transition state of **1a** and **1f**.

conversion of **1a** (entry 3). Byproduct **3a** was not formed in this reaction, reflecting the mild Lewis acidity of $BiCl_3$. Extensive screening revealed that $Bi(OTf)_3$ was the catalyst of choice in terms of both product yield and reaction time (entries 4–6).[10,11] The $PtCl_2$ catalyst, which was the most efficient catalyst for cycloisomerization of 2-ethynylbiaryls, did not promote the reaction (entry 5).[6] Other triflate salts, such as $Cu(OTf)_2$, $Ag(OTf)$, and $In(OTf)_3$, were also tested in this reaction, but none were superior to $Bi(OTf)_3$.[12] The reaction proceeded efficiently in nonpolar solvents such as toluene and hexane, but the yield decreased when Et_2O, THF, MeCN, or DMF was used.[13]

The optimized reaction conditions were applied to the construction of various phenanthrene derivatives (Table 2). The reaction efficiency was sensitive to the electronic features of substituents on the aromatic rings. Vinyl ethers **1b** and **1c**, which contained electron-donating methoxy and electron-neutral methyl groups, respectively, were converted into the corresponding phenanthrenes **2b** and **2c** in excellent yields, even at 25 °C for only 30 min (entries 1 and 2). In contrast, complex product mixtures were obtained from the reaction of vinyl ethers **1d** and **1e**, which contained electron-withdrawing groups (entries 3 and 4), probably due to competitive self-oligomerization via intermolecular addition reaction of the vinyl ethers with the oxocarbenium intermediates generated from **1** (see Scheme 3). The conversion of vinyl ether **1f** (containing a methyl group at the β-carbon of the methoxyethenyl group) to 9-methylphenanthrene **2f** proceeded much faster than the analogous reaction of **1a** leading to phenanthrene **2a** (entry 5 vs Table 1, entry 2). This reactivity difference can be understood by considering that the vinyl ether moiety of **1f** is positioned closer to the phenyl ring in the transition state (Figure 1). Vinyl ether **1g** produced a mixture of the two regioisomers **2g** and **2g′** from reaction at the *para*- and *ortho*-positions, with respect to the methyl group (entry 6). The current reaction system was also applicable to the preparation of **2h** from 2-methoxyethenyl-3-phenylbiphenyl **1h**, which was easily synthesized via palladium-catalyzed C–H bond direct arylation of the aldimine derived from benzaldehyde (entry 7).[14]

This reaction can be applied to the synthesis of other polycyclic aromatic compounds (Figure 2). In general, the regioselectivity of the cyclization is influenced by electronic, not steric, effects. While vinyl ether **1i** potentially could react at either the 2- or 4-position of the 3-thienyl group, naphtho[2,1-*b*]thiophene **2i** was obtained as a single isomer in 97% yield. Its constitutional isomer naphtho[1,2-*b*]thiophene **2i′** can be also synthesized from the cyclization of **1i′** under similar conditions. The cyclization of **1j** also occurred regioselectively to give chrysene **2j** ([4]phenacene) without formation of its constitutional isomer, benz[*a*]anthracene. [4]Helicene **2k** was obtained in 96% yield from the reaction of **1k**. Here, the catalytic activity of $AuCl_3$ proved to be greater than that of $Bi(OTf)_3$. Moreover, double cyclization and aromatization of **1l** proceeded efficiently to afford benzo[*a*]pyrene **2l** in 90% yield.

To investigate the reaction mechanism, several control experiments were conducted (Scheme 2a). Treatment of aldehyde **4**, which might be potentially generated by hydrolysis of **1a**, with a catalytic amount of $Bi(OTf)_3$ gave phenanthrene in 33% yield along with 36% of unreacted **4**. This result indicates that the present reaction does not proceed via formation of aldehyde **4**. When a 56:44 mixture of the *E*/*Z* isomers of **1j** was reacted at 0 °C for 10 min, chrysene **2j** was obtained in 33% yield along with recovery of 66% of **1j** as a 58:42 stereoisomeric mixture (Scheme 2b). The result suggests that both the *E*- and *Z*-isomers of **1j** were consumed at the same rate; the stereochemistry did not affect the reactivity.

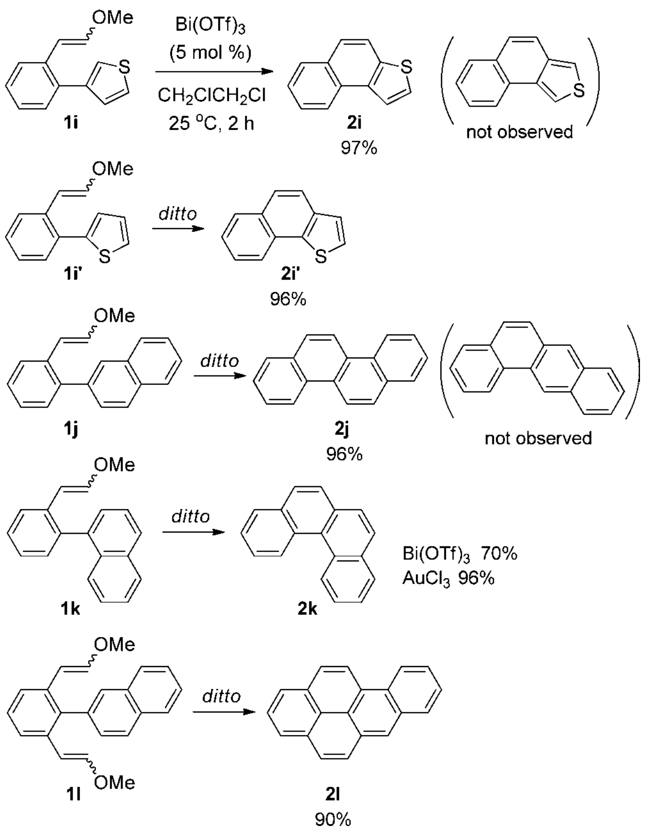
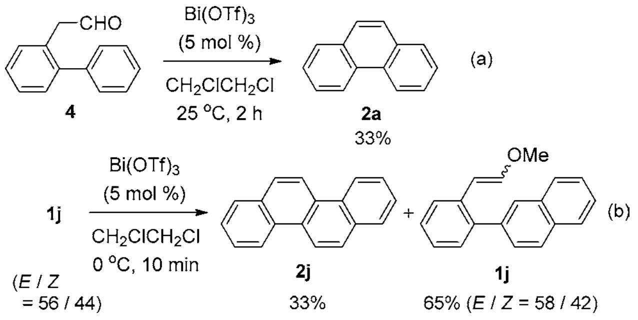


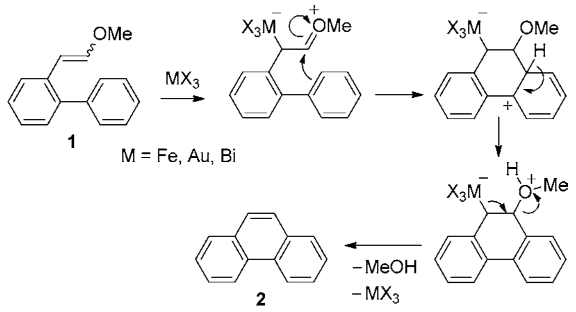
Figure 2. Catalytic synthesis of polycyclic aromatic compounds via regioselective cyclization.

Scheme 2. Control Experiments



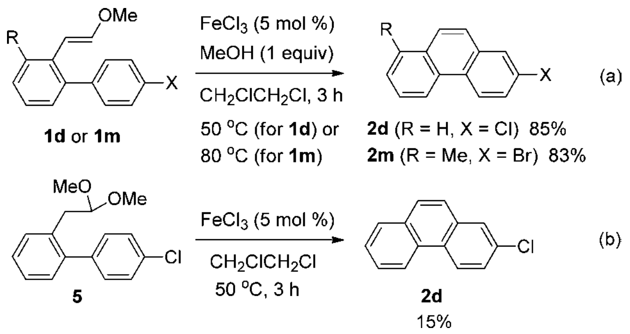
These observations suggest that the transformation proceeds through a Friedel–Crafts electrophilic substitution mechanism via formation of an oxocarbenium ion intermediate. A possible mechanism is shown in Scheme 3, using the formation of phenanthrene as an example. However, an alternative mechanism involving sequential 6π-cyclization and aromatization by elimination of methanol cannot be ruled out. Nevertheless, the former mechanism is plausible because it involves nucleophilic attack of the aromatic ring, which provides a better explanation for the failure of cyclization of **1d** and **1e** with electron-withdrawing substituents (Table 1).

Scheme 3. Proposed Reaction Mechanism



In the course of these studies, we found that the cyclization of vinyl ethers **1d** and **1m** containing electron-withdrawing chloride and bromide groups proceeded efficiently in the presence of $FeCl_3$ following the addition of methanol (Scheme 4a).[15] In this case, the use of $Bi(OTf)_3$ in place of $FeCl_3$ decreased the yield.[16] To understand the role of methanol, the reaction of acetal **5**, which is a potential intermediate derived from **1d**, was conducted (Scheme 4b). Our results indicated that **5** was converted into 2-chlorophenanthrene **2d** in 15% yield, suggesting that the current reaction does not proceed via formation of an acetal intermediate. Thus, the actual reacting species is believed to be $FeCl_n(OMe)_{3-n}$ generated *in situ* when using a combination of $FeCl_3$ and MeOH. The mild Lewis acidity of $FeCl_n(OMe)_{3-n}$ may prevent competitive self-oligomerization via the intermolecular addition reaction of vinyl ethers **1** with the oxocarbenium intermediates generated from **1**. In general, the reactive sites of phenanthrene cores are governed by their electron distribution. Actually, the conventional chlorination of phenanthrene is known to form 9-chlorophenanthrene as the major product together with a mixture of regioisomers,[17] demonstrating the utility of the current new synthetic procedure for access to functionalized PAHs.

Scheme 4. Iron-Catalyzed Synthesis of the Phenanthrenes Having Electron-Withdrawing Chloride and Bromide Groups



In conclusion, a novel bismuth-catalyzed synthesis of PAHs with a phenanthrene backbone has been accomplished from 2-(2-arylphenyl)vinyl ethers. These reactions typically proceeded in excellent yield under mild reaction conditions. Advantages of the current method are the easy availability of the cyclization precursors, operational simplicity, and high reaction efficiency. By choosing an appropriate catalyst system ($Bi(OTf)_3$, $AuCl_3$, or $FeCl_3$/MeOH), the reaction can be used to synthesize phenanthrene derivatives with substituents at various positions. It is clear that the present method provides a new catalytic approach to the synthesis of the carbon skeletal structure of various polycyclic aromatic compounds.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Experimental procedures, spectroscopic data for all new compounds, and copies of ^{1}H and ^{13}C NMR spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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(12) Investigation of several transition-metal catalysts with **1a** in CH_2ClCH_2Cl (0.2 M) at 25 °C for 24 h: Sc(OTf)$_3$, 76% (24 h); [ReBr(CO)$_3$(thf)]$_2$ (2.5 mol%), 83% (24 h); Fe(OTf)$_2$, 21% (24 h); Cu(OTf)$_2$, 88% (2 h); AgOTf, 26% (24 h); BiBr$_3$, 59% (24 h). The following catalysts did not afford **2a** with the recovery of vinyl ether **1a** in >90% yield: Sm(OTf)$_3$, Dy(OTf)$_3$, Re$_2$(CO)$_{10}$, RhCl(PPh$_3$)$_3$, Ir$_4$(CO)$_{12}$, BiI$_3$.

(13) Investigation of solvents: toluene, 92%; hexane, 58%; CHCl$_3$, 10%; Et$_2$O, 65%; THF, 0%; MeCN, 92%; DMF, 0%; neat 17%.

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(15) Treatment of **1a** with 5 mol% of FeCl$_3$ and 1 equiv of methanol at 50 °C for 2 h gave **2a** in 93% yield.

(16) The yield of **2d** was decreased to 40% when the combination of Bi(OTf)$_3$ and MeOH was used as a promoter.

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