

Phenanthrene Synthesis by Iron-Catalyzed [4 + 2] Benzannulation between Alkyne and Biaryl or 2-Alkenylphenyl Grignard Reagent

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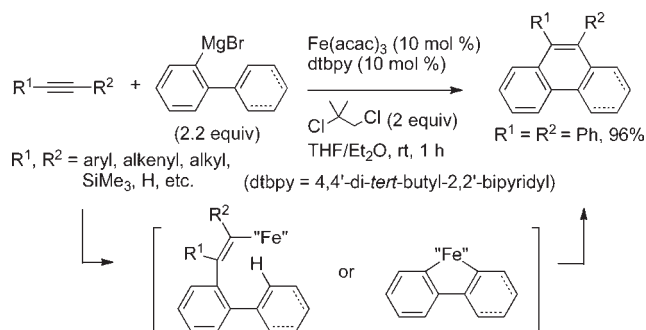
Supporting Information

ABSTRACT: The [4 + 2] benzannulation reaction of internal or terminal alkynes with 2-biaryl, 2-heteroarylphenyl, or 2-alkenylphenyl Grignard reagents in the presence of $\text{Fe}(\text{acac})_3$, 4,4'-di-*tert*-butyl-2,2'-bipyridyl, and 1,2-dichloro-2-methylpropane takes place at room temperature in 1 h to give 9-substituted or 9,10-disubstituted phenanthrenes and congeners in moderate to excellent yields. The reaction tolerates sensitive functional groups such as bromide and olefin. When applied to a 1,3-diyne, the annulation reaction takes place on both acetylenic moieties to give a bisphenanthrene derivative.

Phenanthrene is an important organic structure in materials science,¹ and it is also a partial structure of superconducting picene² and carbon nanotubes.³ Among the numerous synthetic routes to the phenanthrene class of aromatics,^{4–6} the [4 + 2] benzannulation reaction between an alkyne and a biaryl compound has not attracted much attention,^{7,8} despite its ability to create quickly a large variety of phenanthrene compounds. We report herein an iron-catalyzed coupling between an internal or terminal alkyne and a biaryl or alkenylaryl Grignard reagent that forms 9-substituted and 9,10-disubstituted phenanthrenes and congeners in moderate to excellent yields (Scheme 1). The reaction features attractive synthetic attributes such as the use of an inexpensive and environmentally benign iron catalyst,^{9,10} mild reaction conditions, and tolerance of a wide variety of functional groups, including aryl bromide, which are unavailable for similar reactions known in the literature.^{7,8} The method permits the use of 2-furyl- and 2-thienylphenyl Grignard reagents, thereby providing a new synthetic route to naphtho[1,2-*b*]furan and naphtho[1,2-*b*]thiophene. Among various mechanistic possibilities, such as carbometalation¹¹ followed by C–H bond activation¹² or the intermediacy of a biphenyl ferracycle (Scheme 1), evidence favors the latter.

The 1 g scale synthesis of 9,10-diphenylphenanthrene is illustrative (Scheme 1): a mixture of diphenylacetylene (0.98 g, 5.5 mmol) and 2-biphenylmagnesium bromide in Et_2O (20 mL, 0.6 M, 12 mmol) was added dropwise to a solution of $\text{Fe}(\text{acac})_3$ (0.19 g, 0.55 mmol), 4,4'-di-*tert*-butyl-2,2'-bipyridine (dtbpy, 0.15 g, 0.55 mmol), and 1,2-dichloro-2-methylpropane (1.3 mL, 11 mmol) in tetrahydrofuran (THF) (25 mL) at ambient temperature. The reaction mixture was stirred for 1 h to afford 9,10-diphenylphenanthrene in 96% isolated yield, together with a trace amount (<2%) of the 2-vinyl-1,1'-biphenyl derivative. This

Scheme 1. Iron-Catalyzed [4 + 2] Benzannulation



side product suggests the feasibility of the carbometalation pathway but does not exclude the ferracycle pathway.

The reaction was smoothly catalyzed by a variety of iron salts, such as FeCl_3 , $\text{Fe}(\text{acac})_2$, FeCl_2 , and $\text{Fe}(\text{OAc})_2$ having purities ranging from 98 up to 99.995%. When $\text{FeF}_3 \cdot \text{H}_2\text{O}$ was used as the catalyst, a higher temperature (60 °C) and longer reaction time (12 h) were needed to afford the product in 69% yield. Salts of other metals, such as $\text{Pd}(\text{OAc})_2$ and CuI , did not catalyze this reaction at all or were much less effective [$\text{Co}(\text{acac})_2$ and $\text{Ni}(\text{acac})_2$; see the Supporting Information for details]. The reaction required dtbpy (10 mol %) as a ligand and 1,2-dichloroisobutane (2 equiv) as an oxidant,^{12a,b} the absence of which completely shut down the desired reaction and led to partial polymerization of the alkyne.

The reaction stopped at 47% conversion of diphenylacetylene when only 1 equiv of the 2-biphenyl Grignard reagent was used, hence indicating the necessary use of 2 equiv, one for the C–C bond formation and another to accept a hydrogen atom in the C–H bond activation step. The corresponding diarylzinc reagent could also be utilized at the expense of decreased yield (51%).

The scope of the reaction is summarized in Table 1. A variety of alkynes possessing aromatic, alkenyl, alkyl, or trimethylsilyl substituents took part in the annulation reaction in moderate to excellent yield. Diarylacetylenes possessing an electron-withdrawing group (entries 2 and 3) or an electron-donating group (entries 4 and 5) reacted in good to excellent yield. It is notable that chloro and bromo substituents survived the present reaction conditions (entries 2 and 3). We did not find any dehalogenated product or any product arising from a cross-coupling reaction involving the halide group. The reaction therefore shares the same selectivity profile that we found previously.^{12b}

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Table 1. Iron-Catalyzed Annulation of Aryl Grignard Reagents with Alkynes^a

entry	ArMgBr	R ¹	R ²	product	yield (%) ^b
1		Ph	Ph		96 ^c
2		Ph	4-Cl-C ₆ H ₄		77
3		Ph	4-Br-C ₆ H ₄		75
4		Ph	4-MeO-C ₆ H ₄		95
5		Ph	4-Me ₂ N-C ₆ H ₄		95
6 ^d		Ph	(<i>E</i>)-CH=CHPh		79
7 ^d		Ph	CF ₃		69
8		Ph	Me		95
9		<i>n</i> -Pr	<i>n</i> -Pr		91
10		SiMe ₃	SiMe ₃		59
11 ^e		Ph	H		44
12		Ph	Ph		89
13		Ph	Me		93 (55:45)
14 ^{d,f}		Ph	Ph		41
15 ^{d,f}		Ph	Ph		39
16 ^{d,f}		Ph	Ph		85

^a Reaction conditions: a solution of Fe(acac)₃ (10 mol %) and di-*tert*-butyl-2,2'-bipyridyl (10 mol %) in THF (1.0 mL) was added to a solution of alkyne (0.5 mmol) and 1,2-dichloroisobutane (2.0 equiv) in THF (1.0 mL), after which the Grignard reagent (2.2 equiv) was added dropwise. The reaction mixture was stirred at rt for 1 h. See the Supporting Information for details. ^b Isolated yield. ^c The reaction was run on a 1 g scale. ^d A mixture of alkyne and Grignard reagent in ether was added slowly over 10 min. ^e A solution of the alkyne and a solution of the Grignard reagent in diethyl ether were added separately over 10 min. ^f The reaction was performed at 60 °C.

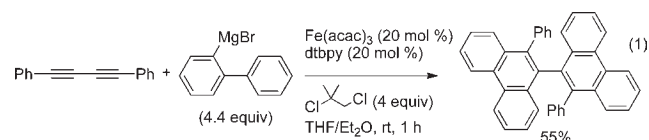
The observed sensitivity of an enyne toward polymerization (data not shown) was attenuated by slow addition of the enyne, and we thus obtained (*E*)-9-phenyl-10-styrylphenanthrene in good yield with retention of the olefin geometry (entry 6). Similarly, trifluoromethylphenylacetylene (entry 7) gave the desired product in good yield when the alkyne was added slowly. 1-Phenylpropyne (entry 8), 4-octyne (entry 9), and bis-(trimethylsilyl)acetylene (entry 10) also reacted in good yield. The silyl groups in the product in entry 10 could serve as a platform for further functionalization. Phenylacetylene could also be utilized under slow-addition conditions (entry 11) to obtain a 9-monosubstituted phenanthrene.

When two nonequivalent ortho hydrogen atoms were available on the aryl Grignard reagent (entries 12 and 13), the reaction took place at the less hindered position.^{12a-c} The

reaction of 1-phenylpropyne with a methyl-substituted biaryl Grignard reagent (entry 13) gave the two expected regioisomers without selectivity (55:45). This lack of regioselectivity contradicts what we would expect from the carbometalation pathway^{11,7d} (Scheme 1, bottom left) but is consistent with the ferracycle path (bottom right). As described in the Supporting Information, D₂O quenching of a reaction between a biaryl Grignard reagent and a stoichiometric amount of Fe(acac)₃ and dtbpy gave back a biaryl showing partial ortho deuteration on both benzene rings, which also provides support for a ferracycle or related intermediate.

2-(2-Thienyl)- and 2-(2-furyl)phenyl Grignard reagents (entries 14 and 15) also took part in the reaction to produce a relatively unexplored type of heteroaromatic system. The reaction using a 2-(cyclohexen-1-yl)phenyl Grignard reagent (entry 16) also proceeded smoothly to give a naphthalene derivative in high yield.

The reaction between 1,4-diphenylbutadiyne and 2-biphenylmagnesium bromide resulted in twofold annulation to give a bisphenanthrene compound (eq 1), further demonstrating the power of this [4 + 2] annulation reaction. This class of congested, twisted aromatic compounds is of considerable interest in the design of organoelectronic devices.¹³ We note in passing that 9,10-diarylphenanthrenes are known¹⁴ to give dibenzo[*g,p*]chrysene derivatives under oxidative thermal conditions, which adds to the utility of the present annulation reaction for the synthesis of functional materials.



In summary, we have developed a new [4 + 2] benzannulation method that allows the coupling of a variety of alkynes with diaryl and related Grignard reagents. Because of the high activity of the iron-based catalytic system, this reaction takes place under mild conditions and enables the construction of sterically congested systems. The oxidative coupling conditions allow the reaction to take place with remarkable chemoselectivity, such as the tolerance of bromide, chloride, trimethylsilyl, trifluoromethyl, and olefinic groups. Some evidence suggests the involvement of a ferracycle intermediate, an intriguing mechanistic possibility under investigation in our laboratory.

■ ASSOCIATED CONTENT

Supporting Information. Experimental procedures and physical properties of the compounds. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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