Alkyne Competition in the Benzannulation Reaction with Chromium Carbene Complexes

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The benzannulation reaction of Fischer carbene complexes is investigated under conditions where the reaction of the carbene complex is occurring in the presence of two different alkynes. A series of competition experiments are examined where the effects of various structural factors are explored by pitting 10 different carbene complexes with 11 different alkynes. Terminal alkynes will react selectively over internal alkynes in all cases examined including both aryl and alkenyl complexes. Aryl carbene complexes with methoxy substituents do not give quite as high selectivity for terminal alkynes over internal alkynes (∼95:5) as do isopropoxy substituents (>99:1), whereas most alkenyl complexes give high selectivity with both substituents (>99:1). Competition experiments between two different terminal alkynes or between two different internal alkynes did not result in anything more than very modest selectivities at best (∼2:1). Excellent selectivities were realized between two different terminal acetylenes if one of the terminal acetylene was protected with a trimethylsilyl group. Finally, it was demonstrated that the high selectivities between terminal and internal alkynes can be utilized in the reaction with molecules that contain both types of alkyne functions.

Introduction

The reaction of chromium carbene complexes with alkynes is one of the most useful methods for the synthesis of phenols and quinones.1 One aspect of the utility of this benzannulation reaction is the very high regioselectivity observed in the reaction with terminal alkynes.2 For example, the reaction of the phenyl complex 1a with phenylacetylene has been reported to give the phenol 2 in 87% yield with no detectable amount of the phenol 3, which would be the result of the other regioisomeric outcome of this reaction (Scheme 1).3 The selectivity was reported to be at least 179:1. Similarly, the reaction of the o-methoxy complex 4 with 1-pentyne has been reported to give the quinone 4 with a >111:1 selectivity over the quinone 5.2a In this case the crude reaction mixture was submitted to an oxidative workup since the isolation of the quinone 4 would be more representative of the true reaction yield than the air-sensitive phenol 6. Unsymmetrical internal alkynes do not give benzannulated products with high levels of regioselectivity unless the steric difference between the two alkynes substituents is large.2 This is illustrated by reactions of the complex 4 with the internal alkynes shown in Scheme 1.2a,4 The regioselectivity is 2.9:1 with n-propyl methyl acetylene2a and increases to only 4.8:1 with isopropyl

methyl acetylene, but with phenyl methyl acetylene a 41:1 selectivity is observed. While the regioselectivity can be affected by steric, the influence of electronics on the benzannulation reaction is not normally observed to any great extent.

The source of the regioselectivity is thought to be related to the relative stability of the isomeric η1,η3-vinyl carbene complexed intermediates 8A and 8B (Scheme 2). According to the best understanding of the mechanism of the benzannulation at this time, these intermediates are generated by a rate-limiting loss of a carbon monoxide ligand from the pentacarbonyl carbene complex 7 and then reaction of the alkyne with the chromium–carbon double bond of the unsaturated intermediate. Calculations reveal that the substituent at the 2-position of these intermediates is much closer to a carbon monoxide ligand than a substituent at the 1-position. Thus as the steric differential between the substituents R_L and R_S increases, intermediate 8A should be increasingly favored over 8B. Subsequent to the formation of the η1,η3-vinyl carbene complexed intermediate 8, the CO insertion to give the ketene complex 9 and then electrocyclic ring closure and tautomerization to give the phenol tricarbonyl complex 10, which can be isolated but is normally oxidized to give either a phenol or quinone product.

Whereas the regioselectivity of the benzannulation reaction of unsymmetrical alkyynes has been studied extensively, the chemoselectivity of a competition between two different alkyynes has not been examined in any systematic fashion.  

Specifically, if the benzannulation of a carbene complex of the type 1a was carried out in the presence of a terminal and an internal alkyne, which product would dominate, the phenol 13 derived from the terminal alkyne or the phenol 14 derived from the internal alkyne (Scheme 3)? From the regioselectivity known for this reaction, it might be suspected that the terminal alkyne would react faster, but this has never been put to the test in a controlled fashion. In the only study that gives some insight in the chemoselectivity of the benzannulation reaction for two different alkyynes, Finn and co-workers found that added alkyynes could affect the product distribution from intramolecular benzannulation reactions without the added alkyynes being incorporated into any of the products. This effect was termed the zenochemical effect. The goal of the present work is to carry out the first systematic

Scheme 1

\[
\begin{align*}
\text{Ph} & \quad \text{Ph} \\
\text{OMe} & \quad \text{OMe} \\
\end{align*}
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Scheme 2

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\text{OMe} & \quad \text{OMe} \\
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TABLE 1. Temperature and Solvent Effects on the Competition between 1-Hexyne and 3-Hexyne

<table>
<thead>
<tr>
<th>entry</th>
<th>carbene complex</th>
<th>temp (°C)</th>
<th>solvent</th>
<th>% yield</th>
<th>15a/16b ratio</th>
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<tr>
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<td>84</td>
<td>93:7</td>
</tr>
<tr>
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<td>1a</td>
<td>80</td>
<td>THF</td>
<td>42</td>
<td>94:6</td>
</tr>
<tr>
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<td>1a</td>
<td>80</td>
<td>MeCN</td>
<td>41</td>
<td>98:2</td>
</tr>
<tr>
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<td>1a</td>
<td>40</td>
<td>benzene</td>
<td>69</td>
<td>95:5</td>
</tr>
<tr>
<td>5</td>
<td>1a</td>
<td>40</td>
<td>THF</td>
<td>35</td>
<td>98:2</td>
</tr>
<tr>
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<td>1a</td>
<td>40</td>
<td>MeCN</td>
<td>33</td>
<td>96:2</td>
</tr>
<tr>
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<td>1b</td>
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<td>benzene</td>
<td>84</td>
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</tr>
<tr>
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<td>1b</td>
<td>80</td>
<td>THF</td>
<td>56</td>
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<td>MeCN</td>
<td>41</td>
<td>99:1</td>
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<tr>
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<td>1b</td>
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<td>1b</td>
<td>40</td>
<td>hexane</td>
<td>79</td>
<td>&gt;99:1</td>
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</tbody>
</table>

*All reactions were carried out with 0.3–0.5 mmol of 1 in 5 mL of solvent with 15 equiv of 1-hexyne and 15 equiv of 3-hexyne. Reaction time was 16 h at 80 °C and 22 h at 40 °C. *Isolated yield by silica gel chromatography. *Determined by GC and GC–MS analysis of the crude reaction mixture. *Trace amounts of 17 and 18 were detected by GC–MS.

study of the competition between two different alkynes in the intermolecular benzannulation of chromium carbene complexes.

Results

It was deemed important to begin the competition under conditions where the concentration of each alkyne would not significantly change even if one of the alkynes were to react in complete preference. Thus, the first experiments were carried out with the carbene complex 1a and 15 equiv of 1-hexyne and 15 equiv of 3-hexyne, and the results are presented in Table 1. The crude reaction mixtures were oxidized by ceric ammonium nitrate, and the ratio of the quinones 15 and 16 were determined by GC–MS analysis of the crude reaction mixture with the aid of authentic samples of each quinone. Small and varying amounts of the indenone 17 and cyclopentendione 18 were detected by GC–MS but were not quantified. In all cases the major product was the quinone 15 resulting from selective reaction with the terminal alkyne with selectivities ranging from a minimum of 93:7 up to >99:1. In each case the yield of quinone 15 was determined by isolation after purification by silica gel chromatography. The chemoselectivity was examined as a function of the temperature (40 or 80 °C), the solvent, and the size of the alkyl group in the alkoxy group of the carbene complex (methyl or isopropyl). The benzannulations of isopropoxy complexes generally give higher yields than methoxy complexes. Several trends are observed from the data in Table 1. First, higher chemical yields are observed in less polar or less coordinating solvents such as benzene or hexane which more than offset the slightly higher selectivities observed in THF and acetonitrile. Second, a clear trend is seen across both the solvent and the nature of the carbene complex that lower temperatures lead to higher selectivity. Thus, for each carbene complex the optimal conditions involve performing the reaction in benzene at 40 °C, which gives a 95:5 selectivity for the methoxy complex 1a (entry 4) and an >99:1 selectivity for the isopropoxy complex 1b (entry 11).

Although the chemoselectivity between the terminal alkyne 1-hexyne and the internal alkyne 3-hexyne is complete (complex 1b) or nearly complete (complex 1a), the fact that 15 equiv of both alkynes was used is not synthetically practical (Table 1). Thus, this competition was repeated with only 1.5 equiv of each alkyne, and the results are shown in Table 2. Remarkably, the selectivities with both carbene complexes in benzene at 40 °C are essentially the same whether 15 equiv or 1.5 equiv of the alkyne is used. A competition was also performed between 1-hexyne and the internal alkyne n-butyl methyl acetylene (2-heptyne), and in this case the selectivity with the methoxy carbene complex 1a is about the same (97:3) as it is with diethyl acetylene (96:4). The isopropoxy complex 1b is completely selective for 1-hexyne over both internal alkynes, showing no detectable amount of the quinone 16 or 19 in the reactions with 3-hexyne or 2-heptyne, respectively.

Like aryl complexes, the benzannulation of alkenyl carbene complexes with alkynes is also a very important reaction in the synthesis of phenols and quinones. Therefore, a series of alkyl carbene complexes shown in Scheme 4 were examined for their ability to undergo chemoselective reactions with terminal alkynes in the presence of internal alkynes. The seven different complexes were subjected to a 1:1 mixture of 1-hexyne and 3-hexyne (1.5–2 equiv of each) in benzene at 40 °C under an argon atmosphere. Upon oxidative workup, the crude reaction mixture was analyzed by GC and/or GC–MS to determine the ratio of products from each alkyne, and then subsequently the major product was isolated in pure form by silica gel chromatography. In each case, the analysis of the


product ratio was aided by an authentic sample of the minor product (22, 27, or 30), which was prepared independently by the reaction of the appropriate carbene complex and 3-hexyne. The results reveal that the methoxy alkenyl complexes give a higher chemoselectivity that the methoxy phenyl complex 1a. In each case the competition results in a 99:1 selectivity in favor of the reaction with the terminal alkyne with the exception of the trans-propenyl complex 23a where a 96:4 ratio is observed. As with the reactions of the aryl complex 1a, analysis of the crude reaction mixtures from the reactions with the alkenyl complexes shown in Scheme 4 by GC–MS reveals the presence of trace amounts of products analogous to 17 and 18. Interestingly, the reaction of the carbene complex 20a gave only a single regioisomer of quinone 21. The quinone 24 would have been formed in this reaction if the regiochemistry of the incorporation of 1-hexyne had been reversed, i.e., formed via intermediate 8B in Scheme 2. We had previously investigated the regioselectivity of complexes 20a and 23a with 1-pentyne in THF and found that the complex 23a is completely regioselective (>99:1), whereas complex 20a only gives a 93:7 selectivity.2c In the present study on the competition of complex 20a with 1-hexyne and 3-hexyne, we observed only the quinone 21 and the regioisomeric quinone 24 could not be detected (<1:99). Given the small difference between 1-pentyne and 1-hexyne, this leads to the conclusion that the complex 20a is much more regioselective with terminal alkynes in benzene than in THF.

Next it was decided to determine if the very high selectivity of the benzannulation reaction for terminal alkynes over internal alkynes could be translated into selectivity between two different terminal alkynes. To maximize the difference in reactivity, the two terminal alkynes were chosen such that the steric difference between the substituents on each alkyne was large. Thus, the reaction of the methoxy phenyl complex 1a was carried out with a 1:1 mixture of tert-butyl acetylene and n-butyl acetylene (1.5 equiv of each), and after oxidative workup, both quinones 15 and 31 were isolated in a 2:1 ratio in a total of 74% yield (Scheme 5). The same selectivity was observed for the alkenyl complex 28. These results suggest that it will not be possible to chemoselectively react a chromium carbene complex with a terminal alkyne in the presence of a second terminal alkyne.

While the difference in the rates of reaction of a terminal acetylene bearing a primary alkyl group and a terminal acetylene bearing a tertiary alkyl group are small but real (Scheme 5), the differences between the rates of an acetylene bearing a primary alkyl group and an acetylene bearing a phenyl group are nonexistent (Scheme 6). This was revealed in the competition between n-butyl acetylene (1-hexyne) and phenyl acetylene which was found to give a 1:1 mixture of quinones 15 and 33 from the phenyl complex 1a and also a 1:1 mixture of quinones 29 and 34 from complex 28. An experiment was also conducted to test the chemoselectivity between two different internal alkynes. The phenyl complex 1a was reacted with 1.5 equiv each of 3-hexyne and 2-heptyne and to give a 1:1 mixture of the quinones 19 and 16. The results in Schemes 5 and 6 taken together indicate that it will not be possible to chemoselectively differentiate between two different terminal alkynes or two different internal alkynes in the benzannulation reaction.

In lieu of a direct discrimination between two different terminal alkynes, it was considered that chemoselection between two different terminal alkynes may be possible if one of the terminal alkynes is protected. Thus, the reaction of alkyn complex 28 was carried out in the presence of 1-hexyne and 1-octyne and different silylated terminal alkynes (Scheme 7). Silicon-substituted alkynes are normal substrates for the benzannulation reaction but in some cases bulky silyl groups can lead to the isolation of ketene complexes rather than the expected benzannulated product.11 We find here that a

silicon substituent provides an excellent method for effecting chemoselection between two different terminal alkynes. This is illustrated in Scheme 7 where it was found that both trimethylsilyl and tert-butyldimethylsilyl groups are sufficient to lead to complete chemoselection between 1-hexyne and 1-pentyne in reaction with the carbene complex 28 when 1-pentyne is protected with a silyl substituent. Both silyl protecting groups provide the quinone 29 in >99:1 selectivity over quinone 35. Under the same conditions, complex 28 will also display complete selection between 1-octyne and trimethylsilyl-1-hexyne giving >99:1 selectivity in favor of quinone 36 over quinone 37. Again the stereoselectivities were determined by GC-MS with the aid of authentic samples of the silylated quinone 35, 37, or 39 that were prepared independently. These competition experiments were deliberately designed such that the silylated and nonsilylated terminal alkynes were not the same. This is because it is possible that the silylated phenol products could suffer protodesilylation to give the phenols 40-42 prior to oxidative workup. In each case it was determined that the quinones from these phenols were not formed. For example, quinone 35 (R = H) was not detected in the reaction where quinone 29 was formed and quinone 29 was not formed in the reaction where 36 was formed. Neither quinone 15 nor quinone 39 was observed in the reaction where quinone 38 was formed, indicating that both aryl and alkenyl complexes can be used in the chemoselective benzannulation of terminal alkynes in the presence of silylated alkynes.

The fact that high chemoselectivity is seen between terminal and internal alkynes with only 1.5 equiv of each alkyne suggests that it should be possible to achieve chemoselectivity in the reactions of molecules containing two different alkyne functions. Indeed, the reaction of the phenyl complex 1a with the diyne 43 gave the quinone 44 in which the terminal alkyne was selectively incorporated (Scheme 8). No evidence for the presence of an isomer of 44 could be detected in the crude reaction mixture by GC-MS analysis. Also, none of the bis-benzannulated product 45 could be detected in the crude reaction mixture by 1H NMR spectroscopy or TLC before quinone 44 was purified.

The two-alkyne annulation provides for a synthesis of phenols starting with an alkyl carbene complex. This reaction can be effected either with 2 equiv of an alkyne in an intermolecular fashion or, more efficiently, with a diyne leading to an intramolecular process. The reaction of the alkyl carbene complex with the first equivalent of the alkyne generates an α,β-unsaturated carbene complex in situ of the type 50 that then undergoes the benzannulation reaction with the second equivalent of the alkyne (Scheme 9). The penultimate product is a cyclohexadienone of the type 53, which can be isolated under certain cases but most often is reduced to a phenol by chromium(0). A few cases are known in which this reaction has been carried out with unsymmetrical diyne, and in each case a single product has been reported and is
that resulting from reaction of the terminal alkyne in preference to the internal alkyne. Neither the presence nor absence of the product resulting from the reaction of the internal alkyne is indicated in these reports. We decided to examine the reaction of the methyl complex 47 with the diyne 43 and determine if, along with the expected phenol 48, we could obtain any evidence for the isomeric phenol 49 that would result from reaction of the internal alkyne first. The optimal solvent for this reaction is THF, and a slightly higher temperature is needed given that CO dissociation from an alkyl carbene complex is slower than for α,β-unsaturated complexes. The reaction of complex 47 with diyne 43 led to the isolation of the phenol 48 in 82% yield. Analysis of the crude reaction mixture by GC−MS and by 1H NMR with the aid of the expected shifts for the phenol 49 led to the conclusion that the phenol 49 is not formed in this reaction or, if it is, the selectivity for 48 over 49 is at least 50:1.

Discussion

The observations made in the present work can be interpreted in terms of the mechanistic scenario outlined in Scheme 10 that can be taken as our best understanding of the possibilities and issues associated with the mechanism of the benzannulation reaction at this point.1,4,5a,6 There seems to be a consensus that the first and rate-limiting step of the benzannulation reaction is loss of CO to give the unsaturated tetracarbonyl complex 54. Although not rate-limiting, the next step involves a bimolecular reaction of intermediate 54 with an alkyne to give either the alkene complex 55 by coordination or, with carbon−carbon bond formation, to give the η1,η1-vinyl carbene complexed intermediate 8A. It is not known conclusively whether the formation of 55 and/or 8A from 54 is reversible or irreversible, although some computational studies suggest that it is not reversible.5d The next step is generally believed to involve an insertion of a carbon monoxide ligand in vinyl carbene complex 8A to give the η1-vinyl ketene complex 9A. There is some evidence to suggest that this CO insertion step is irreversible.4d,12 The origins of the selectivity between 1-hexyne and 3-hexyne must lie either in the kinetic formation of 55 or 8A or, if the formation of 55 and/or 8A are reversible, in the relative stability of 8A derived from 1-hexyne and 3-hexyne. Thermodynamically, 1-hexyne would be expected to give 8A with lower energy given the close contacts between R5 (H vs Et) and the carbon monoxide ligand (8B in Scheme 2) and between R5 and the alkoxy substituent (8A in Scheme 10). The same expectation would pertain to the transition state for the formation of 8A under kinetic conditions. Therefore, the reaction with 1-hexyne would be expected to be more favored and thus much faster.

The chemoselectivity between 1-hexyne and 3-hexyne can be seen to be a function of the size of the alkoxy group. For example, the reaction of methoxy substituted complex 1a gives a 95:5 ratio of quinones 15 to 16 (Table 1, entry 4) whereas, the isopropoxy substituted complex 1b gives complete selectivity for the quinone 15 (≈99:1) as indicated by entry 11 in Table 1. The bulkier isopropoxy group would be expected to induce a stronger interaction with the substituent R5 in the η1,η1-vinyl carbene complexes intermediate 8A than the methoxy group. Thus, differentiation between 1-hexyne (R5 = H) and 3-hexyne (R5 = Et) in the guise of intermediate 8A would be expected to be more pronounced when OR is an isopropoxy group than when it is a methoxy group.

The solvent and temperature both had an effect on the competition between the reactions with 1-hexyne and 3-hexyne as indicated by the data for the reaction with the phenyl complex 1. Although not rate-limiting, the selectivity decreased with increasing temperature (entries 8 vs 11). It was interesting to find that the chemoselectivity increased with the coordinating ability of the solvent, and this was true for both the methoxy and isopropoxy complexes 1a and 1b. This suggests that the 16 e− unsaturated species 54 can be intercepted by solvent to give the saturated intermediate 56. If complex 56 can react with the alkyne in an associative manner to give the η1,η1-vinyl carbene complexed intermediate 8A, then it might be expected that this associative process would be more sensitive to the steric of the alkyne than a process that involves direct coordination of an alkyne with 54 to give 8A.13 This could be expected to lead to increased chemoselection between 1-hexyne and 3-hexyne with coordinating solvents.

The biggest effect of the solvent is the dramatic drop in yields of the quinone 15 (Table 1). It is well-known that the yield of the benzannulation reaction are higher in noncoordinating solvents such as benzene and hexane.1,3b,c,e,g Polar and/or coordinating solvents lead to the formation of several different side-products including indenes46 and cyclobutenones64 and this is certainly a possible explanation for the loss of mass balance in the reactions in THF and MeCN. Indene products were detected by GC−MS in the crude reactions mixtures of the reactions indicated in Table 1, but only the amounts of the quinone 15 were quantified. Cyclobutenones may not survive the thermal conditions of GC analysis.

The benzannulation reactions of alkenyl complexes are well-known to be far less sensitive to solvent than are the reactions of aryl complexes, and this is one of the reasons that the competition reactions for the alkenyl complexes indicated in Scheme 4 were not examined in other solvents. One interesting feature of the reactions in Scheme 4 is that all complexes give complete selection for 1-hexyne over 3-hexyne except for the trans-propenyl complex 23. This may be related to the steric interactions associated with the interaction of an alkene with intermediate 54 and the expectation that they would be larger when R is non-hydrogen than when it is hydrogen.

Conclusions

This study for the first time gives a quantitative look at the relative rate of terminal and internal alkynes in the benzannulation reaction of Fischer carbene complexes. While the alkene is not under normal conditions involved in the rate-limiting step of the reaction, the step at which the alkene is incorporated is apparently much faster for a terminal alkyne than for an internal alkyne. This leads to a greater than 99:1 selectivity for incorporation of the terminal alkyne over the internal alkynyl for most of the carbene complexes studied and the major exception is with aryl methoxy complexes, which display a 95:5 selectivity. This high selectivity includes trimethylsilyl substituted internal alkynes that can serve as surrogates for terminal alkynes since selectivity between different terminal alkynes is low to nonexistent. Armed with the information gained from the present work, the synthetic chemist can proceed with the utmost assurance that the information gained from the present work, the synthetic applications of Fischer carbene complexes employed in this study have been previously described, including the aryl complexes 1a and 1b, the isopropenyl complex 20a, the trans-propenyl complexes 23a and 23b, the sec-butenyl complex 25a, the cyclohexenyl complex 28, and the methyl complex 47.

Preparation of Isopropenyl Isopropoxy Chromium Carbene Complex 20b. To a flame-dried round-bottom flask filled with argon was added isopropenyl bromide (1.8 mL, 20 mmol) in THF (0.1 M). The solution was cooled to −78 °C, and then 1 equiv of n-BuLi was added dropwise. The resulting solution was stirred at −78 °C for 30 min and then transferred by cannula to a flask containing 1.1 equiv of Cr(CO)₆ in THF (0.05 M) at room temperature. The solution was allowed to stir at room temperature for 2 h. The resulting solution of the lithium acylate was concentrated in vacuo and allowed to stand under high vacuum for 10 min. The lithium acylate was dissolved in 20 mL water, and then 1.5 equiv of Me₄NBr was added with vigorously shaking. The solution was stirred at room temperature for 30 min. After this time, the crude ammonium acylate salt was extracted three times with CH₂Cl₂. The organic layer was dried over MgSO₄, and then the solvent was removed in vacuo for 30 min. A portion of the ammonium acylate salt (0.50 g, 1.4 mmol) was dissolved in dry CH₂Cl₂, and 1.5 equiv of freshly prepared isopropyltriflate was added as a concentrated solution in CH₂Cl₂. The reaction was stirred at room temperature for 30 min. The reaction was quenched by pouring the mixture into a separatory funnel containing 25% H₂SO₄, and then extractive work up with CH₂Cl₂. The resulting solution was concentrated in vacuo and the crude product was purified by column chromatography on silica gel to give the desired complex 20b (4.14 g, 12.4 mmol) in 62% yield.

Experimental Section

The preparation and characterization of most of the carbene complexes employed in this study have been previously described, except for the well-known 1,6c,g-trans-2-propenyl complex 23a and the 1,6c,g-trans-3-propenyl complex 23b. This may be related to the steric interactions associated with the interaction of an alkyne with intermediate 54 and the expectation that they would be larger when R is non-hydrogen than when it is hydrogen.

Preparation of Isopropenyl Isopropoxy Chromium Carbene Complex 20b. To a flame-dried round-bottom flask filled with argon was added isopropenyl bromide (1.8 mL, 20 mmol) in THF (0.1 M). The solution was cooled to −78 °C, and then 1 equiv of n-BuLi was added dropwise. The resulting solution was stirred at −78 °C for 30 min and then transferred by cannula to a flask containing 1.1 equiv of Cr(CO)₆ in THF (0.05 M) at room temperature. The solution was allowed to stir at room temperature for 2 h. The resulting solution of the lithium acylate was concentrated in vacuo and allowed to stand under high vacuum for 10 min. The lithium acylate was dissolved in 20 mL water, and then 1.5 equiv of Me₄NBr was added with vigorously shaking. The solution was stirred at room temperature for 30 min. After this time, the crude ammonium acylate salt was extracted three times with CH₂Cl₂. The organic layer was dried over MgSO₄, and then the solvent was removed in vacuo for 30 min. A portion of the ammonium acylate salt (0.50 g, 1.4 mmol) was dissolved in dry CH₂Cl₂, and 1.5 equiv of freshly prepared isopropyltriflate was added as a concentrated solution in CH₂Cl₂. The reaction was stirred at room temperature for 30 min. The reaction was quenched by pouring the mixture into a separatory funnel containing 25% H₂SO₄, and then extractive work up with CH₂Cl₂. The resulting solution was concentrated in vacuo and the crude product was purified by column chromatography on silica gel to give the desired complex 20b (4.14 g, 12.4 mmol) in 62% yield.

References

funnel containing saturated aq NaHCO₃ and pentane. The aqueous layer was separated and extracted with pentane until no red color was seen in the aqueous layer. The combined organic layers were washed twice with brine, and then dried over MgSO₄. The dried solution was filtered through a fritted funnel dry packed with Celite 503. The product carbene complex was purified by silica gel chromatography using pure pentane as eluent to give carbene complex 20b (0.302 g, 0.99 mmol) in 71% yield. Red solid, mp 63–64 °C; R₁ = 0.30 (hexanes). Spectral data for 20b: ¹H NMR (CDCl₃, 500 MHz) δ 1.49 (d, 6 H, J = 5.4 Hz), 1.85 (s, 3 H), 4.83 (br, 1 H), 4.98 (br, 1 H), 5.50 (br, 1 H); ¹³C NMR (CDCl₃, 125 MHz) δ 19.5, 22.7, 85.2, 157.3, 216.4, 224.1, 349.8 (1 s²C not located); IR (neat) 2986, 1456 cm⁻¹; MS m/z (% rel intensity) 304 M⁺ (3), 276 (14), 248 (10), 164 (100), 122 (42). Anal. Calcd for C₁₂H₁₂CrO₆: C, 47.38; H, 3.98. Found: C, 47.36; H, 4.02.

**Preparation of the sec-Butenyl Isopropoxy Chromium Carbene Complex 25b.** Carbene complex 25b was prepared with the same procedure described above for the preparation of carbene complex 20b. The intermediate ammonium acylate salt was obtained in 84% yield. 5.88 g, 16.8 mmol) from (Z)-2-bromobut-2-ene (1.85 mL, 20 mmol). The carbene complex 25b was obtained in 94% yield (0.896 g, 2.81 mmol) from 1.02 g (3.0 mmol) of the ammonium acylate salt. Red oil; R₁ = 0.29 (pentane). Spectral data for 25b: ¹H NMR (CDCl₃, 500 MHz) δ 1.46 (s, 3 H), 1.50 (d, 6 H, J = 6.1 Hz), 1.85 (s, 3 H), 4.93 (br, 1 H), 5.09 (br, 1 H); ¹³C NMR (CDCl₃, 125 MHz) δ 15.0, 20.1, 22.6, 23.03, 83.2, 113.7, 146.1, 216.6, 224.5, 356.3; IR (neat) 2986, 2084, 1786, 1379, 1254, 1178, 1082, 988, 987, 711, 661, 621 cm⁻¹; MS m/z (% rel intensity) 318 M⁺ (1), 178 (31), 175 (41), 174 (42), 107 (28), 105 (20), 84 (100), 83 (83), 80 (18), 67 (26), 55 (93). Anal. Calcd for C₁₃H₁₄CrO₆: C, 49.06; H, 4.43. Found: C, 49.01; H, 4.60.

**Procedure A. Competitive Benzanllination of Carbene Complexes with Two Different Alkynes.** Illustrated for the synthesis of quinone 25b with 3-hexyne. To a 50 mL flame-dried pear-shaped single-necked 15 cm flask was added 1-hexyne (0.75 mL, 6.5 mmol) and 3-hexyne (0.70 mL, 6.2 mmol). The flask was then heated at 40 °C for 22 h (or 80 °C for 2 h). The crude mixture was diluted with Et₂O and treated with 10 equiv of Et₃O. The crude reaction mixture was filtered through a 125 mL separatory funnel containing saturated aq NaHCO₃ and pentane. The aqueous layer was then washed with brine (15 mL), dried over MgSO₄, filtered, and concentrated to 10 mL. The combined organic layers were washed with saturated aq NaHCO₃ and then separated without shaking to avoid an emulsion. The combined organic layers was washed with saturated aq NaHCO₃ (2 × 10 mL). The aqueous layer was then back extracted with ether (2 × 10 mL). The combined organic layers were then washed with brine (15 mL), dried over MgSO₄, filtered, and concentrated in vacuo. The crude product was purified by silica gel chromatography (2 × 25 cm) with 5% EtOAc in hexanes as eluent to give quinone 16 (0.869 g, 0.406 mmol) in 90% yield as a yellow solid. Spectral data for 2,3-diethyl-1,4-benzene-1,4-dione 16: ¹H NMR (CDCl₃, 500 MHz) δ 1.13 (t, 6 H, J = 7.5 Hz), 2.62 (q, 4 H, J = 7.5 Hz), 7.66 (dd, 2 H, J = 5.8, 3.3 Hz), 8.04 (dd, 2 H, J = 5.7, 3.3 Hz); ¹³C NMR (CDCl₃, 125 MHz) δ 14.0, 20.1, 126.1, 132.2, 133.2, 148.1, 185.0. These data match those previously reported for this compound.²¹

**Phenyl Carbene Complexes 1a and 1b with 1-Hexyne and 3-Heptyne.** This competition experiment was carried out with carbene complex 1a (0.107 g, 0.34 mmol), 1-hexyne (0.060 mL, 0.52 mmol), and 3-heptyne (0.058 mL, 0.51 mmol) in 5 mL of benzene at 40 °C for 22 h according to Procedure A to give quinone 15 (0.0540 g, 0.252 mmol) in 78% isolated yield. The ¹H NMR spectrum of the crude reaction mixture indicated that the ratio of 15:16 was 96:4. The same reaction with the isopropoxy carbene complex 1b (0.128 g, 0.38 mmol), 1-hexyne (0.065 mL, 0.57 mmol), and 3-heptyne (0.065 mL, 0.57 mmol) gave 15 (0.0580 g, 0.271 mmol) in 75% yield with a >99:1 ratio of 15:16. The data for 15 matched that presented in Procedure A above.

**Phenyl Carbene Complexes 1a and 1b with 1-Hexyne and 3-Heptyne.** This competition experiment was carried out with carbene complex 1a (0.101 g, 0.32 mmol), 1-hexyne (0.055 mL, 0.48 mmol), and 2-heptyne (0.062 mL, 0.48 mmol) in 5 mL of benzene at 40 °C for 22 h according to Procedure A to give quinone 15 (0.025 g, 0.245 mmol) in 81% isolated yield. The ¹H NMR spectrum of the crude reaction mixture indicated that the ratio of 15:19 was 97:3, which was determined with the aid of an authentic sample of 19 prepared as indicated below. The same reaction with the isopropoxy complex 1b (0.101 g, 0.30 mmol), 15.

Synthesis of Quinone 19 from Phenyl Carbene Complex 1b and 3-Heptyne. This competition experiment was carried out with carbene complex 1b (0.102 mg, 0.30 mmol) and 3-heptyne according to Procedure B. Spectral data for 2-butyl-3-methyl-naphthalene-1,4-dione 19: 1H NMR (CDCl3, 500 MHz) δ 9.3 (t, 3 H, J = 7.1 Hz), 1.41–1.46 (m, 4 H), 2.17 (s, 3 H), 2.61–2.64 (m, 2 H), 7.66–7.68 (m, 2 H), 8.05–8.07 (m, 2 H); 13C NMR (CDCl3, 125 MHz) δ 12.6, 13.9, 23.1, 26.8, 30.9, 126.2, 126.3, 132.2, 132.2, 133.3, 133.3, 143.1, 147.6, 184.7, 185.4. These data match those previously reported for this compound.22

Isopropenyl Carbone Complexes 20a and 20b with 1-Heptyne and 3-Heptyne. This competition experiment was carried out with carbene complex 20a (0.170 g, 0.616 mmol), 1-heptyne (0.141 mg, 1.23 mmol), and 3-heptyne (0.140 mg, 1.23 mmol) in 6.2 mL of benzene at 40 °C for 22 h according to Procedure A to give quinone 21 (0.0642 g, 0.360 mmol) in 62% isolated yield. The 1H NMR spectrum of the crude reaction mixture indicated that the ratio of 21:22 was 99:1, which was determined with the aid of an authentic sample of 22 prepared as described below. The same reaction with the isopropoxy complex 20b (0.268 g, 0.842 mmol), 1-heptyne (0.145 mg, 1.26 mmol), and 3-heptyne (0.143 mg, 1.26 mmol) in 8.4 mL of benzene gave 26 (0.1270 g, 0.66 mmol) in 83% yield with a > 99:1 ratio of 26:27. Spectral data for 5-n-butyl-2,3-dimethylcyclohexa-2,5-diene-1,4-dione 26: 1H NMR (CDCl3, 300 MHz) δ 0.85 (t, 3 H, J = 7.1 Hz), 1.28–1.43 (m, 4 H), 1.93 (s, 3 H), 1.95 (s, 3 H), 2.33 (t, 2 H, J = 7.4 Hz), 6.42 (s, 1 H); 13C NMR (CDCl3, 75 MHz) δ 12.0, 13.8, 22.3, 28.7, 29.9, 131.9, 140.4, 145.0, 187.4, 187.5. These data those previously reported for this compound.24

Synthesis of Quinone 27 trans-sec-Butenyl Carbone Complex 25b and 3-Heptyne. Quinone 27 was prepared from carbene complex 25b and 3-hexyne according to Procedure B. Spectral data for 2,3-diethyl-5,6,7,8-tetrahydronaphthalene-1,4-dione 27: 1H NMR (CDCl3, 500 MHz) δ 0.4 (t, 6 H, J = 7.6 Hz), 1.98 (s, 6 H), 2.46 (q, 4 H, J = 7.6 Hz); 13C NMR (CDCl3, 125 MHz) δ 12.3, 14.0, 19.7, 140.4, 145.0, 187.5. These data matched those previously reported for this compound.26

Cyclohexenyl Carbone Complex 28 with 1-Heptyne and 3-Heptyne. This competition experiment was carried out with carbene complex 28 (0.16 g, 0.5 mmol), 1-heptyne (0.115 mL, 1.0 mmol), and 3-heptyne (0.114 mL, 1.0 mmol) in 5 mL of benzene at 40 °C for 22 h according to Procedure A to give quinone 29 (0.075 g, 0.344 mmol) in 72% isolated yield. The 1H NMR spectrum of the crude reaction mixture indicated that the ratio of 29:30 was 99:1, which was determined with the aid of an authentic sample of 30 as prepared described below. Spectral data for 2,3-diethyl-5,6,7,8-tetrahydronaphthalene-1,4-dione 29: 1H NMR (CDCl3, 500 MHz) δ 0.90 (td, 3 H, J = 7.3, 1.8 Hz), 1.33–1.37 (m, 2 H), 1.65–1.67 (m, 4 H), 2.36–2.40 (m, 2 H), 2.64 (q, 4 H, J = 7.4 Hz); 13C NMR (CDCl3, 125 MHz) δ 13.7, 14.0, 19.5, 21.2, 22.5, 22.6, 28.5, 29.9, 131.9, 141.9, 142.3, 149.0, 187.5, 187.7. These data those previously reported for this compound.25

Phenyl Carbone Complex 1a with n-Butyl Acetylene and tert-Butyl Acetylene. This competition experiment was carried out with carbene complex 1a (0.247 g, 0.79 mmol), 1-heptyne (0.136 mL, 1.19 mmol), and tert-butyl acetylene (0.142 mL, 1.19 mmol) in 8 mL of benzene at 40 °C for 22 h according to Procedure A to give quinone 15 (0.079 g, 0.369 mmol) in 49% isolated yield and quinone 31 (0.040 g, 0.187 mmol) in 25% isolated yield. The 1H NMR spectrum of the crude reaction mixture indicated that the ratio of 15:31 was 2:1. The data for 15 matched that those presented for 15 in

Cyclohexenyl Carbene Complex 28 with 1-Hexyne and Trimethylsilyl-1-pentyne. This competition experiment was carried out with carbene complex 28 (0.158 g, 0.50 mmol), 1-hexyne (0.086 mL, 0.75 mmol), and 1-TMS-1-pentyne (0.138 mL, 0.75 mmol) in 5 mL of benzene at 40 °C for 22 h according to Procedure A to give quinone 29 (0.0848 g, 0.406 mmol) in 81% isolated yield as the only product. The 1H NMR spectrum of the crude reaction mixture indicated that the ratio of 29:55a was >99:1 as determined with the aid of an authentic sample of quinone 55a prepared as described below. Quinone 55a also could not be detected by GC—MS analysis of the crude reaction mixture. The data for quinone 29 match those presented for 29 above.

Synthesis of Quinone 35a from Carbene Complex 28 and Tri- methylsilyl-1-pentyne. Quinone 35a (45 mg, 0.145 mmol, 44%) was prepared from carbene complex 28 (103 mg, 0.33 mmol) and trimethylsilyl-1-pentyne according to Procedure B. Yellow oil; Rf = 0.51 (20:1:1 hexanes/Et2O/CH2Cl2). Spectral data for 6,7,8-tri- (trimethylsilyl)-3- propynaphthalene-1,4-dione 35a: 1H NMR (CDCl3, 500 MHz) δ 0.26 (s, 9 H), 0.93 (s, 3 H, J = 7.3 Hz), 1.35—1.40 (m, 20 H), 1.62—1.64 (m, 4 H), 2.33—2.37 (m, 4 H), 2.45—2.48 (m, 2 H); 13C NMR (CDCl3, 125 MHz) δ 1.6, 14.3, 21.1, 21.2, 22.5, 26.4, 27.3, 30.7, 141.9, 143.5, 145.5, 156.5, 186.8, 192.0; IR 2942, 2874, 1444, 1273, 1468, 844 cm⁻¹; MS m/z (rel intensity) 276 M⁺ 34 (36), 262 (22), 261 (100), 233 (26). HRMS (CI) calcd for C16H22O2Si3 [M+3H]⁺ 277.1624, meas 277.1619.

Cyclohexenyl Carbene Complex 28 with 1-Hexyne and tert-Butyldimethylsilyl-1-pentyne. This competition experiment was carried out with carbene complex 28 (0.158 g, 0.50 mmol), 1-hexyne (0.086 mL, 0.75 mmol), and 1-TBS-1-pentyne (0.138 mL, 0.75 mmol) in 5 mL of benzene at 40 °C for 22 h according to Procedure A to give quinone 29 (0.0848 g, 0.389 mmol) in 78% isolated yield as the only product. No evidence for the presence of quinone 35b could be obtained upon analysis of the crude reaction mixture by GC—MS or 1H NMR spectroscopy. The data for quinone 29 match those presented for 29 above.

Cyclohexenyl Carbene Complex 28 with 1-Octyne and Trimethylsilyl-1-hexyne. This competition experiment was carried out with carbene complex 28 (0.0778 g, 0.25 mmol), 1-octyne (0.0404 mL, 0.38 mmol), and 1-TMS-1-hexyne (0.075 mmol) in 5 mL of benzene at 40 °C for 22 h according to Procedure A to give quinone 29 (0.0484 g, 0.389 mmol) in 80% isolated yield as a yellow oil; Rf = 0.30 (20:1:1 hexanes/Et2O/CH2Cl2). The 1H NMR spectrum of the crude reaction mixture indicated the presence of only traces of quinone 29 (0.0848 g, 0.389 mmol) in 78% isolated yield as the only product. No evidence for the presence of quinone 35b could be obtained upon analysis of the crude reaction mixture by GC—MS or 1H NMR spectroscopy. The data for quinone 29 match those presented for 29 above.

Cyclohexenyl Carbene Complex 28 with 1-Cyclohexyl and Trimethylsilyl-1-hexyne. This competition experiment was carried out with carbene complex 28 (0.0778 g, 0.25 mmol), 1-cyclohexyl (0.0404 mL, 0.38 mmol), and 1-TMS-1-hexyne (0.075 mmol) in 5 mL of benzene at 40 °C for 22 h according to Procedure A to give quinone 29 (0.0848 g, 0.389 mmol) in 78% isolated yield as the only product. No evidence for the presence of quinone 35b could be obtained upon analysis of the crude reaction mixture by GC—MS or 1H NMR spectroscopy. The data for quinone 29 match those presented for 29 above.

Phenyl Carbene Complex 1a with n-Butyl Acetylene and Phenyl Acetylene. This competition experiment was carried out with carbene complex 1a (0.158 g, 0.50 mmol), 1-hexyne (0.086 mL, 0.75 mmol), and phenyl acetylene (0.082 mL, 0.75 mmol) in 5 mL of benzene at 40 °C for 22 h according to Procedure A to give quinone 33 (0.0204 g, 0.087 mmol) in 18% isolated yield in a 55:45 isolated ratio. The 1H NMR spectrum of the crude reaction mixture indicated that the ratio of 33:55 was 1:1. The data for 33 matched those presented for 35 in Procedure A above. Spectral data for 2-phenylacetyl-5,6,7,8-tetrahydro-[1,4]naphthoquinone 35: 1H NMR (CDCl3, 500 MHz) δ 0.29 (s, 9 H), 1.35—1.40 (m, 20 H), 1.62—1.64 (m, 4 H), 2.33—2.37 (m, 4 H), 2.45—2.48 (m, 2 H); 13C NMR (CDCl3, 125 MHz) δ 125.8, 126.7, 131.4, 132.7, 133.7, 133.8, 143.5, 148.0, 184.3, 185.0. These data matched those previously reported for this compound.

Phenyl Carbene Complex 1a with 3-Hexyne and 2-Heptyne. This competition experiment was carried out with carbene complex 1a (0.102 g, 0.33 mmol), 2-heptyne (0.076 mL, 0.66 mmol), and 3-hexyne (0.075 mL, 0.66 mmol) in 5 mL of benzene at 40 °C for 22 h according to Procedure A. The quinones could not be separated by chromatography on silica gel, and thus purification resulted in the isolation of a 1:1 mixture of 19 and 16 in a 62% combined yield (0.046 g of the mixture). The quinones were identified in the mixture with the aid of the 1H NMR spectra of each of the quinones, which were prepared as described above.
isolated in 55% yield. Spectral data for 2-nmixture stirred for 45 min at -butyl-2,3-dihydroinden-1-one (35.3 mg, 0.188), which was prepared as described below. Spectral data for 2-hexyl-

Synthesis of Quinone 39 from Phenyl Carbene Complex 1a and Trimethylsilyl-1,6-hexene. Quinone 39 (27.8 mg, 0.087 mmol, 25%) was prepared from carbene complex 1a (107 mg, 0.343 mmol) and trimethylsilyl-1,6-hexene according to Procedure B. The major product of this reaction was tentatively identified as 3-n-butyl-2,3-dihydroinden-1-one (35.3 mg, 0.188), which was isolated in 55% yield. Spectral data for 2-n-butyl-3-(trimethylsilyl)naphthalene-1,4-dione 39: 1H NMR (CDCl 3 , 500 MHz) δ 0.83-0.86 (m, 3 H), 1.25-1.29 (m, 4 H), 1.34-1.37 (m, 1 H), 1.50-1.55 (m, 2 H), 2.50-2.53 (m, 2 H), 6.74 (t, J = 1.4 Hz), 7.66-7.68 (m, 2 H), 7.99-8.01 (m, 1 H), 8.03-8.05 (m, 1 H); 13C NMR (CDCl 3 , 125 MHz) δ 13.0, 13.3, 13.5, 13.6, 13.9, 14.7, 16.1, 16.4, 17.2, 25.2, 27.9, 28.0, 29.5, 31.5, 105.9, 126.0, 126.3, 130.2, 130.3, 133.4, 133.5, 146.4, 151.9, 185.1, 185.2. These data match those previously reported for this compound.21

Preparation of 1,6-Octadiyne 43. 1-Trimethylsilyl-1,6-octadiyne (3.34 g, 18.7 mmol) was dissolved in 100 mL of dry THF, and then 20 mL of 1 M TBAF solution was added via syringe. The solution turned dark brown immediately. The mixture was stirred for 1 h at room temperature. Then, 30 mL of a saturated aqueous ammonium chloride solution was added, and the aqueous layer was extracted with diethyl ether. The combined organic phase was dried with MgSO 4 and then filtered. The solvent was evaporated on rotary evaporator, and then the residue was passed through silica gel with pentane to remove a brown residue. The pentane was removed under vacuum yielding 1,6-octadiyne 43 in 51% yield (1.02 g, 9.6 mmol) as a colorless liquid. The overall yield from 1,6-heptadiyne was 41% over 3 steps. On large scale the product can be distilled at bp 65-70 °C (15 Torr). Spectral data for 43: 1H NMR (CDCl 3 , 500 MHz) δ 1.65 (pent, J = 7.0 Hz, 2 H), 1.73 (t, J = 2.7 Hz, 3 H), 1.91 (t, J = 3 Hz, 1 H), 2.12 (m, 2 H), 2.27 (m, 2 H); 13C NMR (CDCl 3 , 125 MHz) δ 3.4, 17.5, 17.8, 27.9, 68.6, 77.0, 77.9, 83.7; IR (KBr) 3420w, 2958s, 2925vs, 1453w, 1454w, 1157w, 10671.

Benzannulation of Phenyl Carbene Complex 1a with 1,6-Octa-
diyne 43. The reaction of carbene complex 1a (0.2123 g, 0.68 mmol) and alkyne 43 (0.1083 g, 1.02 mmol) in 10 mL of dry benzene was carried out following Procedure B described above at 40 °C for 22 h. After the reaction was done, 10 equiv of a 0.5 M aqueous solution of ceric ammonium nitrate was added at room temperature along with 10 mL of diethyl ether, and resulting mixture was stirred for 6 h. Then, the reaction mixture was washed with aq NaHCO 3 , and the aqueous layer was separated and extracted with Et 2 O. The combined organic layers were dried over MgSO 4 , and the volatiles were removed by rotary evaporation. Analysis of the crude reaction mixture by GC–MS and 1H NMR did not provide any evidence for the presence of quinone 46 or for quinone 45. GC–MS analysis was performed on an Agilent JW Scientific DB-5 ms column (0.32 mm × 30 m) with an initial temperature of 60 °C with a ramp rate of 10 °C/min. Quinone 44 had a retention time of 12.48 min, but otherwise the baseline was flat from 2 to 18 min. Finally, quinone 44 was purified by preparative TLC (hexane/EtOAc = 5:1) on an Analtech 20 × 2 cm 1000 μm plate to give 0.1182 g of yellow needles (50% mmol, 73%). Spectral data for 44: 1H NMR (CDCl 3 , 500 MHz) δ 1.74 (t, J = 2.5 Hz, 3 H), 1.78 (pent, J = 7.5 Hz, 2 H), 2.24 (m, 2 H), 2.69 (dt, J = 7.5 Hz, 1 H, 2 H), 6.83 (t, J = 1 Hz, 1 H), 7.48 (2 H, J = 7.0 Hz, 2 H), 7.37 (m, 2 H), 8.07 (m, 1 H), 8.10 (m, 1 H); 13C NMR (CDCl 3 , 125 MHz) δ 3.4, 18.4, 27.2, 27.8, 76.8, 78.1, 126.1, 126.6, 132.2, 133.1, 133.3, 148.8, 159.4, 184.6, 189.6. These data match those previously reported for quinone 50.22

Synthesis of 1,6-Octadiyne 43 from 1,6-Heptadiyne. Preparation of 1-Trimethylsilyl-1,6-heptadiyne. 1,6-Heptadiyne (2.0 g, 21 mmol) was dissolved in 100 mL of dry THF, cooled to -78 °C, and then allowed to stir at this temperature for 10 min. A solution of lithium diisopropylamide (6.9 mL of benzene at 40 °C) and the aqueous phase was extracted with diethyl ether. After dichloromethane. All fractions were collected and combined, purified by preparative TLC (hexane/EtOAc=5:1) on an Analtech JW Scientific DB-5 ms column (0.32 mm × 30 m) with a ramp rate of 10 °C/min. 1,6-Octadiyne 43 was obtained in 89% yield (3.34 g, 18.7 mmol) as a colorless liquid. Spectral data: 1H NMR (CDCl 3 , 500 MHz) δ 0.14 (s, 9 H), 1.68 (pent, J = 7 Hz, 2 H), 1.77 (t, J = 3 Hz, 3 H), 2.21-2.24 (m, 2 H), 2.34-2.30 (m, 2 H).

Two-Alkyne Annulation of Methyl Carbene Complex 47 with 1,6-Octa-
diyne 43. The reaction of the carbene complex 47 (0.2126 g, 0.85 mmol) and the diyne 43 (0.1062 g, 1.02 mmol) in 23 mL of dry tetrahydrofuran was carried with Procedure B indicated above. After 16 h at 70 °C, the reaction was complete, the solution was transferred to a 50 mL flask, and 10 g of silica gel was added. The volatiles were removed by rotary evaporator for 30 min, and then the resulting impregnated silica gel powder was placed on top of 10 g of silica gel in a column and eluted with dichloromethane. All fractions were collected and combined, and the 1H NMR spectrum of the crude reaction mixture was

(bp 95–102 °C, 15 Torr) to yield 1-trimethylsilyl-1,6-octadiyne in 89% yield (3.34 g, 18.7 mmol) as a colorless liquid. Spectral data: 1H NMR (CDCl 3 , 500 MHz) δ 0.14 (s, 9 H), 1.68 (pent, J = 7 Hz, 2 H), 1.77 (t, J = 3 Hz, 3 H), 2.21-2.24 (m, 2 H), 2.34-2.30 (m, 2 H).
recorded. The $^1$H NMR spectrum of the crude reaction mixture without filtering through silica gel is subject to severe signal broadening due to the presence of paramagnetic Cr(III) species. The phenol 48 was then purified by silica gel chromatography to give 48 in 82% yield (0.1142 g, 0.70 mmol). Spectral data for 48: $^1$H NMR (CDCl$_3$, 500 MHz) $\delta$ 2.05 (pent, $J = 7.5$ Hz, 2 H), 2.22 (s, 3 H), 2.80 (t, $J = 7.5$ Hz, 2 H), 2.83 (t, $J = 7.5$ Hz, 2 H), 2.17 (s, 3 H), 4.43 (s, 1 H), 6.85 (s, 1 H); $^{13}$C NMR (CDCl$_3$, 125 MHz) $\delta$ 12.4, 16.1, 25.3, 31.8, 32.6, 119.0, 120.7, 123.4, 135.3, 142.2, 150.4. HRMS (ES$^-$) calcd for (C$_{11}$H$_{14}$O$^-$ - H)$^+$ m/z 161.0966; meas 161.0970. Yellow needles mp 79°C. $R_f = 0.47$ (5:1 hexane/EtOAc).

Analysis of the $^1$H NMR spectrum of the crude reaction mixture indicates that the phenol 48 is the exclusive product of the reaction and that the ratio of phenol 48 to phenol 49 is at least 50:1. The phenol 49 is a known compound, and the $^1$H NMR spectrum of 49 is reported to have an aromatic singlet at 6.50 ppm. 32 The aryl singlet for the phenol 48 determined in the present work occurs at 6.85 ppm. This type of chemical shift difference is typical of what is expected for the shielding effect of a hydroxyl group on a benzene ring. For example, the pair of compounds 2,3,4,6-tetramethylphenol 70a (aryl singlet at 6.78 ppm) and 2,3,4,5-tetramethylphenol 70b (aryl singlet at 6.49 ppm) and the pair of compounds 2,4-dimethylethra-2-lol 71a (singlet at 6.62 ppm) and 3,4-dimethylethra-2-lol 71b (singlet at 6.33–6.36 ppm) also exhibited shielding effects of the hydroxyl group in the range of ~0.3 ppm. Analysis of the $^1$H NMR spectrum of the crude reaction mixture revealed that there were no absorptions visible in the range of 6.3–6.6 ppm, and thus it can be concluded that the selectivity for phenol 48 over 49 is at least 50:1.

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Supporting Information Available: $^1$H and $^{13}$C spectra of the compounds discussed in this work. This material is available free of charge via the Internet at http://pubs.acs.org.