

Cobalt-Mediated Intermolecular Allyl/Alkyne [3 + 2] Cycloaddition Reactions. A Practical Metal Template for Convergent Synthesis of Functionalized Seven-Membered Rings

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Transition metal-mediated cycloaddition reactions provide synthetic access to important organic ring systems inaccessible by traditional cycloaddition methodology.² Seven-membered-ring synthesis is prominent among these efforts, with important recent advances in two-component cycloadditions and intramolecular cyclization methodology.³ Our investigation is focused on the development of metal-mediated allyl/alkyne cycloaddition reactivity patterns, targeting intermolecular three-component cyclization processes.⁴ η^3 -Allyl alkyne coupling reactions proceed via vinyl olefin intermediates and typically provide open-chain η^5 -pentaadienyl complexes⁵ (path a) or η^5 -cyclopentadienyl complexes⁶ (path b) from reaction with a single alkyne (Scheme 1). Incorporation of two alkynes has also been reported, leading to the formation of η^1, η^4 -methanocyclohexadiene complexes (path c).⁷ By controlling the regiochemistry of the migratory insertion that determines ring size in the double alkyne reactions, we recently established the first allyl/alkyne cycloaddition reactions to yield seven-membered-ring systems with high selectivity (path d).^{8,9} To exploit the synthetic potential of that iridium-mediated reactivity pattern, less expensive and more reactive organometallic systems were sought for the development of organic methodology.

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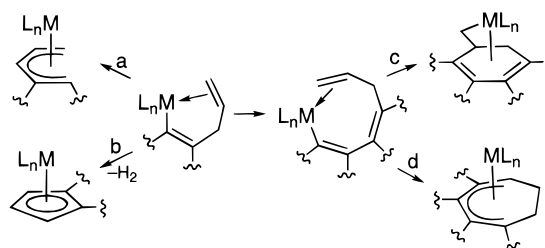
(6) (a) Lutsenko, Z. L.; Aleksandrov, G. G.; Petrovskii, P. V.; Shubina, E. S.; Andrianov, V. G.; Struchkov, Yu. T.; Rubezhov, A. Z. *J. Organomet. Chem.* **1985**, *281*, 349. (b) Nehl, H. *Chem. Ber.* **1993**, *126*, 1519.

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(8) Schwiebert, K. E.; Stryker, J. M. *J. Am. Chem. Soc.* **1995**, *117*, 8275.

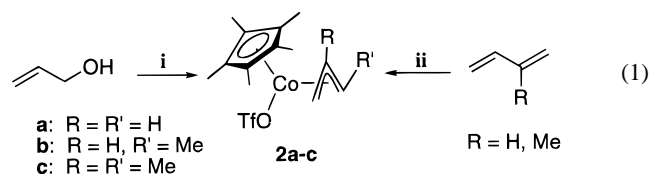
(9) Mn(allyl)₂/ α, ω -diyne cycloaddition gives mixtures of six- and seven-membered-ring dienes: Tang, J.; Shinokubo, H.; Oshima, K. *Organometallics* **1998**, *17*, 290. In contrast, iridium-mediated allyl/ α, ω -diyne cycloaddition provides seven-membered-ring formation exclusively.⁸

Scheme 1



In this communication, we report that unsaturated permethylcyclopentadienylcobalt(III) allyl complexes react with alkynes to give substituted η^5 -cycloheptadienyl complexes by metal-mediated intermolecular [3 + 2 + 2] cycloaddition. Subsequent nucleophilic alkylation/decomplexation procedures provide functionalized organic cycloheptadienes in a highly regioselective and stereoselective manner, providing convergent new methodology for the construction of synthetically valuable seven-membered-ring systems.

The required cobalt(III) η^3 -allyl complexes can be generated in several ways compatible with the development of synthetic organic methodology.¹⁰ The neutral η^3 -allylcobalt triflate complexes **2** are particularly convenient precursors, with good thermal stability, high solubility, and a highly labile triflate ligand (eq 1). The unsubstituted allyl triflate complex **2a** is prepared in high



Conditions: i. (C₅Me₅)Co(C₂H₄)₂ (**1**), TfOH, Et₂O, -78 °C → RT, 4h
ii. (C₅Me₅)Co(C₂H₄)₂ (**1**), hexane, 65 °C, 4–12h; then step i.

yield by treatment of allyl alcohol with (C₅Me₅)Co(ethylene)₂ (**1**)¹¹ and triflic acid. The red-brown inner-sphere triflate complex **2a** thus formed can be used in situ or isolated in 85–90% yield.^{12,13} Substituted η^3 -allyl derivatives are best prepared from the 1,3-diene by thermal exchange followed by protonation, without isolation of the intermediate diene complex (eq 1). Thus, η^3 -crotyl and η^3 -1,2-dimethylallyl triflate complexes **2b** and **2c**^{12–14} are formed in near-quantitative yield and can be isolated in crystalline form in yields in excess of 80%.

Consistent with a previous report,^{6b} permethylcyclopentadienylcobalt η^3 -allyl complexes react with alkynes in THF to yield substituted cyclopentadienyl complexes by dehydrogenative [3 + 2] cycloaddition, even in the presence of excess alkyne. By using a noncoordinating solvent, however, the reaction is diverted to the higher-order cycloaddition, producing seven-membered-ring complexes from incorporation of two equivalents of alkyne (Table 1). Thus, treatment of allyl, crotyl, and 1,2-dimethylallyl complexes **2a–c** in dichloromethane with excess acetylene affords

(10) (a) Allyl halide/(C₅Me₅)Co(ethylene)₂, followed by Ag(I) ionization: Brestensky, D. M. Ph.D. Dissertation, Indiana University, 1992. (b) Oxidation or oxidative halogenolysis/Ag(I) ionization of cobalt(II) allyl complexes: Reference 6b.

(11) Nicholls, J. C.; Spencer, J. L. *Inorg. Synth.* **1990**, *28*, 278. Frith, S. A.; Spencer, J. L. *Inorg. Synth.* **1985**, *23*, 15.

(12) Complete experimental, spectroscopic, and analytical data are provided in the Supporting Information.

(13) Triflate complexes **2** show solvent-dependent infrared spectroscopy¹² similar to that observed for the isostructural inner-sphere iridium triflate complex: Schwiebert, K. E.; Stryker, J. M. *Organometallics* **1993**, *12*, 600.

(14) The allyl ligands are assigned the exo configuration based on difference NOE spectroscopy.¹²

Table 1. [3 + 2 + 2] Allyl/Alkyne Cycloaddition^a

Entry	Allyl complex/ precursor	Alkyne	Product	Yield ^b
1	2a	H≡C-H	3a (R, R' = H)	52 (66)
2	2b	H≡C-H	3b (R = H, R' = Me)	79 (85)
3	2c	H≡C-H	3c (R, R' = Me)	80
4	2a	Ph≡C-H	3d	59
5	2a	^t Bu≡C-H	3e	88
6 ^c		H≡C-H	3f (n = 1)	47
7 ^c		H≡C-H	3g (n = 2, BF ₄ salt)	59

^aConditions: CH₂Cl₂, excess alkyne (PhC≡CH, 3 equiv; ^tBuC≡CH, 10 equiv), -78 °C→RT, 12h. ^bYield of spectroscopically homogeneous material obtained from chromatography. Yields in parenthesis are overall yields obtained from complex **1**, without isolation of the allyl triflate complex **2**. ^cConditions: i. (C₅Me₅)Co(C₂H₄)₂ (**1**), THF, 0 °C→RT 6h; ii. AgOTf or AgBF₄, HC≡CH, acetone, RT, 0.5h.

η^5 -cycloheptadienyl complexes **3a–c** as air-stable solids in good yield (entries 1–3).¹² No formation of η^5 -cyclopentadienyl or η^1, η^4 -methanocyclohexadiene products is observed, nor are significant amounts of regioisomeric η^5 -cycloheptadienyl complexes detected in the crude product. The endo stereochemistry of the methyl substituent in complexes **3b** and **3c** is assigned by spectroscopic correlation with the structure and stereochemistry of bicyclic complex **3f**, which was confirmed unambiguously by X-ray crystallography.¹² The use of terminal alkynes also leads to the formation of η^5 -cycloheptadienyl complexes (entries 4 and 5), although phenylacetylene and 3,3-dimethyl-1-butene provide regioisomeric substitution patterns in complexes **3d** and **3e**.^{15,16} Synthetically interesting bicyclic complexes **3f** and **3g** can also be prepared, starting from readily available five- and six-membered-ring precursors (entries 6 and 7). In these cases, oxidative addition is used to prepare the η^3 -allyl complexes, which are converted without isolation by *in situ* ionization and treatment with acetylene.

Conversion of η^5 -cycloheptadienyl complexes **3** to organic cycloheptadiene derivatives is accomplished by nucleophilic alkylation^{17,18}/oxidative decomplexation (Table 2).¹⁹ Sodium dimethylmalonate, for example, adds regioselectively to the unsubstituted end of the pentadienyl fragment, providing func-

(15) The use of propyne produces an inseparable mixture of η^5 -cycloheptadienyl isomers; the use of trimethylsilylacetylene produces only desilylated η^5 -cyclopentadienyl complex. Dimethyl acetylenedicarboxylate appears not to coordinate to the electrophilic cobalt center.

(16) Disubstituted alkynes undergo more complicated transformations, which will be discussed in a separate account: Dzwiniel, T. L.; Etkin, N. E.; Stryker, J. M., in preparation.

(17) Nucleophilic additions to [(C₅H₅)Co(η^5 -cycloheptadienyl)]⁺: (a) Salzer, A.; Bigler, P. *Inorg. Chim. Acta* **1981**, *48*, 199. (b) Maguire, L. A. P.; Mouncher, P. A.; Salzer, A. *J. Organomet. Chem.* **1988**, *347*, 383. (c) Wieser, M.; Karaghiosoff, K.; Beck, W. *Chem. Ber.* **1993**, *126*, 1081.

Table 2. Synthesis of Functionalized Cycloheptadienes

Cyclo-adduct	Diene complex ^a	Yield ^b	Free Diene ^c	Yield ^d
3a	4a (R, R' = H)	71	5a (R, R' = H)	67
3b	4b (R = H, R' = Me)	63	5b (R = H, R' = Me)	62
3c	4c (R, R' = Me)	89	5c (R, R' = Me)	49
3d	4d	72	5d	50
3g	4g	96	5g	62

^aConditions: NaCH(CO₂Me)₂, THF, RT, 4h. ^bYield of spectroscopically homogeneous material obtained from pentane extraction under N₂ and used without further purification. ^cConditions: [(C₅H₅)₂Fe]⁺PF₆⁻ (2.5 equiv), CH₃CN/pentane, -35 °C→RT, 5–10 min. ^dYield is of isolated pure material obtained from flash chromatography.

functionalized diene complexes **4**¹² with complete stereoselectivity.^{20–22} Demetallation is more difficult than in the less-electron-rich cyclopentadienylcobalt systems¹⁹ but is accomplished in reasonable yields by using ferrocenium salts and a two-phase solvent system.¹² The dienes are obtained without positional isomerization as the exclusive organic product; the material balance consists of intractable material and the known dication [(C₅Me₅)Co(NCCH₃)₃]²⁺(PF₆⁻)₂.²³ It is noteworthy that the trans stereochemical relationship observed for the cycloheptadiene substituents in **5b**, **5c**, and **5g** is complementary to that obtained by conventional metal-mediated functionalization sequences starting from the unsubstituted η^5 -cycloheptadienyl ring.¹⁸

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Supporting Information Available: Experimental procedures, complete spectroscopic and analytical data, tables of comparative NMR spectroscopy, and details of the crystal structure determination for complex **3f** (40 pages, print/PDF). See any current masthead page for ordering information and Web access instructions.

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(18) The synthetic organic chemistry of η^5 -cycloheptadienyl iron complexes has been developed, starting with a preformed seven-membered ring: (a) Pearson, A. J. *Iron Compounds in Organic Synthesis*; Academic Press: New York, 1994; Chapter 5. (b) Pearson, A. J.; Kole, S. L.; Ray, T. *J. Am. Chem. Soc.* **1984**, *106*, 6060.

(19) Oxidative decomplexation of cobalt η^4 -cycloalkadiene complexes: Gelsing, E. R. F.; Tane, J. P.; Vollhardt, K. P. C. *Angew. Chem., Int. Ed. Engl.* **1980**, *19*, 1023. Tane, J. P.; Vollhardt, K. P. C. *Angew. Chem., Int. Ed. Engl.* **1982**, *21*, 617. Macomber, D. W.; Verma, A. G.; Rogers, R. D. *Organometallics* **1988**, *7*, 1241.

(20) Malonate anion deprotonates sterically hindered complex **3e**, producing the η^4 -1,4-di-*tert*-butylcycloheptatriene complex.

(21) The potential for sequential polyalkylation procedures is demonstrated by the conversion of diene complex **4a** to [(C₅Me₅)Co(6-malonyl- η^5 -cycloheptadienyl)]⁺BF₄⁻ upon treatment with Ph₃C⁺BF₄⁻ (CH₂Cl₂, room temperature, 60%).^{12,18}

(22) The addition of LiEt₃BH (THF, -78 °C) to **3a–c** provides nonconjugated η^4 -cyclohepta-1,4-diene complexes.^{17a}

(23) Fairhurst, C.; White, C. *J. Chem. Soc., Dalton Trans.* **1979**, 1524.