Novel Michael Additions to Phenols Promoted by Osmium(II): Convenient Stereoselective Syntheses of 2,4- and 2,5-Cyclohexadienones

Michael E. Kopach and W. Dean Harman*

Contribution from the Department of Chemistry, University of Virginia, Charlottesville, Virginia 22901

Received March 8, 1994®

Abstract: A series of alkylated phenols (phenol, *p*- and *o*-cresol, 4-methoxy- and 3,4-dimethoxyphenol, 5,6,7,8-tetrahydro-2-naphthol, and β-estradiol) are complexed with pentaammineosmium(II) and treated with a variety of Michael acceptors (e.g., MVK, methyl acrylate, acrylonitrile, *N*-methylmaleimide, and 3-butyn-2-one). Under both acidic and basic reaction conditions, a single conjugate addition takes place either ortho or para to the hydroxy group to generate stable 2,4- or 2,5-cyclohexadien-1-one complexes, respectively. For phenol the conjugate addition occurs exclusively at C(4) for all Michael acceptors investigated. For cases where C(4) is substituted, the regioselectivity depends on reaction conditions and the nature of the electrophile, but examples of selective addition at both C(4) and C(6) are reported. When the sp^3 carbon of the resulting cyclohexadienone is a methine, the ligand may be rearomatized and removed from the metal by moderate heating (70–80 °C). When the sp^3 carbon is quaternary, stable dienone products may be obtained by oxidative removal of the metal with Ce(IV) or DDQ, and a number of substituted arene and dienone products are synthesized by this methodology in good overall yield (54–83%).

Introduction

In principle, aromatic molecules are excellent synthons for highly functionalized alicyclic compounds. They are widely available, highly stable, and readily derivatized through substitution, and most significantly, they constitute cyclic skeletons composed entirely of unsaturated carbons. The successful utilization of arenes as precursors to more saturated systems often depends on a chemist's ability to dearomatize them selectively. Methods for achieving this, such as the Birch reduction, have become powerful tools in the synthesis of natural products.[1]

The chemical nature of aromatic systems is profoundly affected by their coordination to transition metals,[2-4] and the utility of η^6-arene complexes in organic synthesis has been widely demonstrated.[3,4] Much of the success realized in this application can be attributed to the high degree of regio- and stereocontrol offered; the metal serves not only to activate the organic substrate but to direct chemical agents to the face of the ring opposite the metal. By utilizing *dihapto-coordinated* arenes in organic transformations, an additional advantage is gained in that the coordination of two carbons disrupts the aromaticity of the organic ligand,[5] thereby imparting a diene-like reactivity to the uncoordinated ring carbons.[6]

Recently, we demonstrated that η^2-coordination of phenol to Os(II) significantly alters the chemical nature of the aromatic ring.[7] Through a substantial "back-bonding" interaction, the osmium(II) has the effect of both localizing the π-electron density in the uncoordinated portion of the arene and stabilizing the 2,4- and 2,5-diene-1-one products resulting from electrophilic addition.[8] In particular, we find that Michael additions to the ring of η^2-coordinated phenol complexes may be accomplished with great facility and with a high degree of both regio- and stereocontrol to generate a variety of 2,4- and 2,5-cyclohexadienone complexes. These species may be demetalated to give the dienone in good overall yield. A portion of this study has been previously communicated.[9]

Experimental Section

Infrared spectra were recorded on a Mattson Cygnus 100 FTIR spectrometer as KBr pellets or glazes. ^{13}C and ^1H NMR spectra were obtained on a General Electric QE300 (300 MHz) or GN300 (300 MHz) spectrometer unless otherwise specified and are reported in ppm vs tetramethylsilane. The multiplicities of ^{13}C NMR resonances are supported by DEPT. Electrochemical experiments were performed under nitrogen using a PAR model 362 potentiostat driven by a PAR model 175 universal programmer. Cyclic voltammograms were recorded (Kipp & Zonen X-Y recorder) in a standard three-electrode cell from +1.5 to −1.5 V with a glassy carbon working electrode. All potentials are reported vs NHE and, unless otherwise noted, were determined in acetonitrile (~0.5 M tetra-*n*-butylammonium hexafluorophosphate (TBAH)) using ferrocene ($E_{1/2}$ = 0.55 V), decamethylferrocene ($E_{1/2}$ = 0.04 V), or cobaltocenium hexafluorophosphate ($E_{1/2}$ = −0.78 V) *in situ* as a calibration standard. The peak-to-peak separation ($E_{p,a}$–$E_{p,c}$) was between 60 and 80 mV for all reversible couples reported, and the scan rate was 100 mV/s unless otherwise noted. All reported yields are for isolated, crude materials unless otherwise specified. This work was carried out under a nitrogen atmosphere in a Vacuum Atmospheres Co. glovebox.

Abbreviations: OTf = $CF_3SO_3^-$; DME = 1,2 dimethoxyethane; MVK = methyl vinyl ketone; DIEA = *N*,*N*-diisopropylethylamine; DMAc = *N*,*N*-dimethylacetamide; DDQ = 2,3-dichloro-5,6-dicyano-1,4-benzoquinone; de = diastereomeric excess.

® Abstract published in *Advance ACS Abstracts*, June 15, 1994.

(1) (a) Mander, L. N. *Synlett* **1991**, 134. (b) Mander, L. N.; Hook J. M. *Nat. Prod. Rep.* **1986**, 37.

(2) (a) Pike, R. D.; Sweigart, D. A. *Synlett* **1990**, 565. (b) Semmelhack, M. F. *Comparative Organic Synthesis* Semmelhack, M. F., Ed.; Pergamon: New York, 1992; Vol. 4. (c) Kane-Maguire, L. A. P. *Chem. Rev.* **1984**, *84*, 525. (d) Cleak, G. R.; Garcia, J. L.; Harrison, J. J.; Thebtaranonth, Y.; Wulff, W.; Yamashita, Y. *Tetrahedron* **1981**, *37*, 3957.

(3) Collman, J. P.; Hegedus, L. S.; Norton, J. R.; Finke, R. G. *Principles and Applications of Organotransition Metal Chemistry*, 2nd ed.; University Science Books: Mill Valley, CA, 1987; Chapter 20.

(4) Davies, S. G. *Organotransition Metal Chemistry: Applications to Organic Synthesis;* Pergamon Press: Oxford, U.K., 1982; Vol. 2.

(5) (a) Muetterties, E. L.; Bleeke, J. R.; Wucherer, E. J. *Chem. Rev.* **1982**, *82*, 499. (b) Heijden, H. v. d.; Orpen, A. G.; Pasman, P. *J. Chem. Soc., Chem. Commun.* **1985**, 1576. (c) Harman, W. D.; Gephart, M.; Taube, H. *Inorg. Chem.* **1990**, *29*, 567.

(6) (a) Harman, W. D.; Taube, H. *J. Am. Chem. Soc.* **1988**, *110*, 7555. (b) Harman, W. D.; Taube, H. *J. Am. Chem. Soc.* **1990**, *112*, 2682. (c) Harman, W. D.; Taube, H. *J. Am. Chem. Soc.* **1988**, *110*, 7906.

(7) Kopach, M. E.; Hipple, W. G.; Harman, W. D. *J. Am. Chem. Soc.* **1992**, *114*, 1736.

(8) Kopach, M. E.; Gonzalez, J.; Harman, W. D. *J. Am. Chem. Soc.* **1991**, *113*, 8972.

(9) Kopach, M. E.; Kelsh, L. P.; Harman, W. D. *J. Am. Chem. Soc.* **1993**, *115*, 5322.

0002-7863/94/1516-6581$04.50/0

Reagents. $[Os(NH_3)_5(OTf)](OTf)_2$ was synthesized as described by Lay et al.[10] $[Os(NH_3)_5(\eta^2\text{-L})](OTf)_2$ complexes where L = phenol (I),[7] *p*-cresol (II),[7] *o*-cresol (III),[7] and β-estradiol (XX)[9] have been previously reported. Compounds XXI and XXII also have been previously reported.[9] All metal-containing compounds were purified by ion-exchange chromatography and precipitated as BPh_4^- salts unless otherwise specified.[11] Methanol was dried by distillation over $Mg(OMe)_2$ prepared *in situ* from Mg^0 and I_2 under nitrogen. Magnesium powder was activated under nitrogen in a DME solution of iodine for 1 h followed by copious washing with DME, DMAc, and Et_2O. Anhydrous ether was dried by distillation over sodium metal and benzophenone. Methylene chloride was distilled from P_2O_5. Acetonitrile was distilled from CaH_2. 1,2-Dimethoxyethane (Aldrich Anhydrous) and acetone were degassed but otherwise used as supplied. All other reagents were used as purchased without further purification. All solvents were deoxygenated by purging with nitrogen.

$[Os(NH_3)_5(4\alpha\text{-(3-oxobutyl)-}2\beta,3\beta\text{-}\eta^2\text{-2,5-cyclohexadien-1-one})](OTf)_2$ (IV). The η^2-phenol complex I (102.4 mg, 0.153 mmol) was dissolved in CH_3CN (600 mg). Methyl vinyl ketone (10.8 mg, 0.154 mmol) was added, and the reaction mixture was stirred for ~1.5 h before direct addition to CH_2Cl_2 (100 mL). A tan precipitate formed (102 mg, 91%) which was collected, washed with ether, and dried *in vacuo*. ^1H NMR (CD_3CN): δ 6.60 (d, 1H, J = 10 Hz), 5.70 (d, 1H, J = 10 Hz), 4.68 (br s, 3H, *trans*-NH_3), 4.05 (d, 1H, J = 8.0 Hz), 3.85 (d, 1H, J = 8.0 Hz), 3.30 (br s, 12 H, *cis*-NH_3), 3.10 (m, 1H), 2.60 (m, 2H), 2.38 (d, 1H, J = 1.0 Hz), 2.08 (s, 3H), 2.00 (m, 1H). ^{13}C NMR (CD_3CN) δ 209.3 (CO), 199.9 (CO), 150.0 (CH), 130.5 (CH), 55.8 (CH), 51.9 (CH), 40.1 (CH), 38.4 (CH_2), 30.9 (CH_3), 30.6 (CH_2). Cyclic voltammetry: $E_{p,a}$ = 0.93V. IR: ν_{CO} = 1636, 1701 cm^{-1}. Anal. Calcd for $C_{58}H_{67}O_2N_5B_2Os\cdot H_2O$: C, 63.56; H, 6.34; N, 6.34. Found: C, 63.40; H, 6.16; N, 6.39.

4-(4-Hydroxyphenyl)-2-butanone. Compound IV (70.1 mg, 0.095 mmol) was dissolved in CD_3CN (500 mg) and heated to 70 °C in an NMR tube. The progress of decomplexation was monitored by ^1H NMR. After 6 h the reaction was complete and the solution had darkened. The reaction mixture was treated with H_2O (20 mL) then extracted with ether (3 × 30 mL) and CH_2Cl_2 (1 × 30 mL). The combined extracts were dried over anhydrous magnesium sulfate and evaporated to dryness. A clear oil (13.0 mg, 83%) was isolated whose ^1H and ^{13}C NMR resonances matched those of the authentic material. ^1H NMR ($CDCl_3$): δ 7.02 (d, 2H, J = 8.8 Hz), 6.75 (d, 2H, J = 8.8 Hz), 5.95 (br s, 1H), 2.80 (t, 2H), 2.73 (t, 2H), 2.13 (s, 3H). ^{13}C NMR ($CDCl_3$): δ 209.2 (CO), 154.6 (C), 130.0 (C), 129.8 (2CH), 115.8 (2CH), 45.9 (CH_2), 45.8 (CH_2), 29.4 (CH_3).

$[Os(NH_3)_5(4\alpha\text{-(}N\text{-methylsuccinimid-3-yl)-}2\beta,3\beta\text{-}\eta^2\text{-2,5-cyclohexadien-1-one})](OTf)_2$ (V). The η^2-phenol complex I (100.4 mg, 0.150 mmol) and *N*-methylmaleimide (43.0 mg, 0.387 mmol) were dissolved in CH_3CN (500 mg). Pyridine (12.0 mg, 0.151 mmol) was added, and the reaction was allowed to stir for ~2 h, after which time the reaction mixture turned red. The reaction mixture was then added directly to ether (20 mL) to give a tan precipitate (115 mg, 98%) which was washed with CH_2Cl_2 and ether and dried *in vacuo* (de > 90%). ^1H NMR (CD_3CN): δ 6.50 (d, 1H, J = 10 Hz), 5.97 (d, 1H, J = 10 Hz), 4.29 (br s, 3H, *trans*-NH_3), 4.21 (d, 1H, J = 8.0 Hz), 4.17 (d, 1H, J = 8.0 Hz), 3.51 (m, 1H), 3.18 (br s, 12 H, *cis*-NH_3), 3.06 (m, 1H), 2.87 (s, 3H), 2.75 (d of d, 1H, J = 18.0 Hz), 2.35 (d of d, 1H, J = 18.0 Hz). ^{13}C NMR (CD_3CN): δ 199.6 (CO), 177.9 (CO), 176.7 (CO), 145.2 (CH), 133.5 (CH), 53.8 (CH), 51.8 (CH), 44.9 (CH), 39.9 (CH), 30.5 (CH_2), 28.7 (NCH_3). Cyclic voltammetry: $E_{p,a}$ = 0.95 V. Anal. Calcd for $C_{59}H_{66}O_3N_6B_2Os\cdot H_2O$: C, 62.32; H, 6.03; N, 7.39. Found: C, 62.68; H, 6.03; N, 7.43.

$[Os(NH_3)_5(4\alpha\text{-(3-oxocyclopentyl)-}2\beta,3\beta\text{-}\eta^2\text{-2,5-cyclohexadien-1-one})](OTf)_2$ (VI). The η^2-phenol complex I (73.0 mg, 0.109 mmol) was dissolved in CH_3CN (850 mg). 2-Cyclopenten-1-one (17.0 mg, 0.207 mmol) followed by pyridine (34.0 mg, 0.430 mmol) was added and the reaction stirred for 6 h, over which time it turned deep red. The reaction mixture was then added directly to ether (20 mL) to yield a tan precipitate (65 mg, 79%) which was washed with CH_2Cl_2 and ether and dried *in vacuo* (de > 90%). ^1H NMR (CD_3CN): δ 6.81 (d, 1H, J = 9.0 Hz), 5.92 (d, 1H, J = 9.0 Hz), 4.43 (br s, 3H, *trans*-NH_3), 4.28 (d, 1H, J = 7.8 Hz), 4.11 (d, 1H, J = 7.8 Hz), 3.12 (br s, 12 H, *cis*-NH_3), 3.10 (m, 1H), 2.60 (m, 2H), 1.70–2.50 (m, 5H). ^{13}C NMR (CD_3CN): δ 218.5 (CO), 199.8 (CO), 149.1 (CH), 131.2 (CH), 55.0 (CH), 52.4 (CH), 43.1 (CH), 43.0 (CH), 41.8 (CH_2), 38.6 (CH_2), 27.1 (CH_2). Cyclic voltammetry: $E_{p,a}$ = 0.95 V. Anal. Calcd for $C_{59}H_{67}O_2N_5B_2Os\cdot H_2O$: C, 63.95; H, 6.28; N, 6.32. Found: C, 63.96; H, 6.48; N, 6.73.

$[Os(NH_3)_5(4\alpha\text{-(4-oxo-}sec\text{-butyl)-}2\beta,3\beta\text{-}\eta^2\text{-2,5-cyclohexadien-1-one})](OTf)_2$ (VII). The η^2-phenol complex I (147 mg, 0.220 mmol) was dissolved in CH_3CN (900 mg) to form a dark orange solution. DIEA (24.0 mg, 0.186 mmol, 0.845 equiv) was added followed by crotonaldehyde (37 mg, 0.52 mmol), and the reaction mixture was stirred 10 min before direct addition to ether (20 mL). A light tan solid (135 mg, 83%) was collected and dried *in vacuo*. ^1H NMR revealed a 1:1 ratio of diastereomers. Spectroscopic data for both diastereomers are reported. ^1H NMR (CD_3CN, both isomers combined): δ 9.75 (m, 2H), 6.77 (d of d, 1H, J = 9.9 Hz), 6.75 (d of d, 1H, J = 9.9 Hz), 5.94 (d, 2H, J = 9.9 Hz), 4.46 (br s, 6H, *trans*-NH_3), 4.18 (m, 4H), 3.14 (br s, 24 H, *cis*-NH_3), 2.30–3.50 (m, 8H), 1.15 (d, 3H), 1.10 (d, 3H). ^{13}C NMR (CD_3CN, both isomers combined): δ 203.3 (CO), 203.2 (CO), 200.2 (CO), 200.1 (CO), 149.1 (CH), 148.7 (CH), 131.8 (CH), 131.5 (CH), 55.5 (CH), 54.6 (CH), 53.0 (CH), 52.8 (CH), 48.0 (CH), 47.2 (CH), 44.5 (CH), 44.3 (CH), 32.9 ($2CH_2$), 16.9 (CH_3), 16.0 (CH_3). Cyclic voltammetry: (both isomers combined): $E_{p,a}$ = 1.00 V. Anal. Calcd for $C_{58}H_{67}O_2N_5B_2Os$: C, 64.50; H, 6.44; N, 6.48. Found: C, 64.39; H, 6.29; N, 6.66.

$[Os(NH_3)_5(4\alpha\text{-(4-oxo-}sec\text{-butyl)-}6\beta\text{-methyl-}2\beta,3\beta\text{-}\eta^2\text{-2,5-cyclohexadien-1-one})](OTf)_2$ (VIII). The η^2-*o*-cresol complex III (100 mg, 0.147 mmol) was dissolved in CH_3CN (900 mg) to form a dark orange solution. Crotonaldehyde (20 mg, 0.289 mmol) was added followed by pyridine (10 mg, 0.126 mmol), and the reaction mixture was stirred for 26 h before direct addition to ether (20 mL). A light orange solid (105 mg, 95%) was collected and dried *in vacuo*. ^1H NMR revealed a 4:1 ratio of diastereomers (de = 60%). Characterization data are reported for the major diastereomer only. ^1H NMR (DMSO-d_6): δ 9.70 (t, 1H), 6.50 (s, 1H), 4.40 (br s, 3H, *trans*-NH_3), 4.10 (m, 2H), 3.44 (m, 1H), 3.15 (br s, 12 H, *cis*-NH_3), 2.50 (m, 2H), 2.23 (s, 1H), 1.80 (s, 3H), 1.10 (d, 3H). ^{13}C NMR (CD_3CN): δ 204 (CO), 199 (CO), 142 (CH), 137 (C), 54.0 (CH), 52.1 (CH), 48.0 (CH_2), 43.0 (CH), 32.0 (CH_2), 17.0 (CH_3), 16.0 (CH_3). Cyclic voltammetry: $E_{p,a}$ = 0.96 V. Anal. Calcd for $C_{59}H_{69}O_2N_5B_2Os\cdot 3.5\,H_2O$: C, 61.35; H, 6.63; N, 6.06. Found: C, 61.33; H, 6.50; N, 6.26.

$[Os(NH_3)_5(4\alpha\text{-(2-(carbomethoxy)ethyl)-}2\beta,3\beta\cdot\eta^2\text{-2,5-cyclohexadien-1-one})](OTf)_2$ (IX). The η^2-phenol complex I (55 mg, 0.082 mmol) and zinc triflate (60.0 mg, 0.165 mmol) were dissolved in CH_3CN (700 mg). Methyl acrylate (24 mg, 0.274 mmol) then DIEA (10.0 mg, 0.077 mmol) were added, and the reaction mixture was allowed to stir for 13 h, over which time the solution turned deep red. A light orange precipitate (50 mg, 81%) was obtained by adding the reaction mixture directly to ether (~100 mL) followed by filtration and drying *in vacuo*. ^1H NMR (CD_3CN): δ 6.78 (d, 1H, J = 10 Hz), 5.89 (d, 1H, J = 10 Hz), 4.43 (br s, 3H, *trans*-NH_3), 4.27 (d, 1H, J = 8.0 Hz), 4.11 (d, 1H, J = 8.0 Hz), 3.61 (s, 3H), 3.13 (br s, 12 H, *cis*-NH_3), 2.45–2.60 (m, 3H), 2.15 (m, 2H). ^{13}C NMR (CD_3CN): δ 200.2 (CO), 174.1 (CO), 151.0 (CH), 130.1 (CH), 56.3 (CH), 52.1 (CH), 51.6 (OCH_3), 38.7 (CH), 31.3 (CH_2), 30.5 (CH_2). Cyclic voltammetry: $E_{p,a}$ = 0.95 V. Anal. Calcd for $C_{58}H_{67}O_3N_5B_2Os\cdot H_2O$: C, 62.64; H, 6.25; N, 6.30. Found: C, 62.49; H, 5.81; N, 6.32.

$[Os(NH_3)_5(4\alpha\text{-(2-cyanoethyl)-}2\beta,3\beta\text{-}\eta^2\text{-2,5-cyclohexadien-1-one})](OTf)_2$ (X). The η^2-phenol complex I (270 mg, 0.404 mmol) and zinc triflate (147 mg, 0.405 mmol) were dissolved in CH_3CN (1.8 g). Acrylonitrile (34 mg, 0.640 mmol) then DIEA (20.0 mg, 0.155 mmol) were added, and the reaction mixture was allowed to stir for 24 h, over which time the solution darkened. A light orange solid (99%, 290 mg) was obtained upon addition to ether (~100 mL) and drying *in vacuo*. ^1H NMR (CD_3CN): δ 6.62 (d, 1H, J = 10 Hz), 5.72 (d, 1H, J = 10 Hz), 4.68 (br s, 3H, *trans*-NH_3), 4.04 (d, 1H, J = 7.5 Hz), 3.88 (d, 1H, J = 7.5 Hz), 3.32 (br s, 12 H, *cis*-NH_3), 3.10 (m, 1H), 2.50–2.70 (m, 2H), 2.48 (m, 1H), 2.38 (m, 1H). ^{13}C NMR (CD_3CN): δ 199.5 (CO), 148.6 (CH), 131.0 (CH), 121.4 (CN):, 54.2 (CH), 51.5 (CH), 38.2 (CH), 31.8 (CH_2), 14.2 (CH_2). Cyclic voltammetry: $E_{p,a}$ = 0.93 V. Anal. Calcd for $C_{57}H_{64}ON_6B_2Os\cdot H_2O$: C, 63.45; H, 6.17; N, 7.79. Found: C, 63.54; H, 6.05; N, 7.57.

$[Os(NH_3)_5(4\alpha\text{-(3-oxobutyl)-}4\beta\text{-methyl-}2\beta,3\beta\text{-}\eta^2\text{-2,5-cyclohexadien-1-one})](OTf)_2$ (XI). The η^2-*p*-cresol complex II (52.7 mg, 0.077 mmol) was dissolved in CH_3CN (530 mg). This solution was treated with MVK (234 mg, 3.39 mmol) then DIEA (22mg, 0.17 mmol)

(10) Lay, P.; Magnuson, R.; Sen, J.; Taube, H. *J. Am. Chem. Soc.* **1982**, *104*, 7658.

(11) In all cases the crude metal complex was dissolved in ~0.2 M NaCl and loaded onto a Sephadex ion-exchange column. Elution with 0.2 M NaCl gave dark red bands which were treated with excess sodium tetraphenylborate. Light colored precipitates were obtained which were filtered, washed with H_2O, and dried *in vacuo*.

and stirred for 1 h before being added to ether (20 mL). A tan precipitate (55 mg, 95%) formed which was collected, washed with ether, and dried *in vacuo*. ^{1}H NMR (CD_3CN): δ 6.54 (d, 1H, J = 10.1 Hz), 5.79 (d, 1H, J = 10.1 Hz), 4.42 (br s, 3H, *trans*-NH_3), 4.27 (d, 1H, J = 7.6 Hz), 4.16 (d, 1H, J = 7.6 Hz), 3.56 (m, 1H), 3.24 (br s, 12 H, *cis*-NH_3), 2.95 (m, 1H), 2.40 (m, 1H), 2.06 (s, 3H), 2.00 (m, 1H), 1.11 (s, 3H). ^{13}C NMR (CD_3CN): δ 208.8 (CO), 199.2 (CO), 155.5 (CH), 129.6 (CH), 57.8 (CH), 52.9 (CH), 42.5 (C), 39.0 (CH_2), 38.8 (CH_2), 29.8 (CH_3), 24.2 (CH_3). Cyclic voltammetry: $E_{p,a}$ = 0.92 V. Anal. Calcd for $C_{59}H_{69}O_2N_5B_2Os\cdot H_2O$: C, 63.84; H, 6.45; N, 6.31. Found: C, 63.80; H, 6.19; N, 6.20.

Synthesis of **XI** on an open lab bench. A 50-mL Erlenmeyer flask was charged with a stir bar, methanol (15 g), and $Os(NH_3)_5(OTf)_3$ (1.00 g, 1.39 mol) and flushed with argon. (No attempts were made to rigorously dry solvents or glassware prior to their use.) A solution of *p*-cresol (250 mg, 2.31 mmol) in CH_3OH was added followed immediately by Zn/Hg^0 (3 g), at which point the flow of argon was discontinued and the flask was sealed with a septum. After 1 h of stirring, the dark solution was treated with MVK (160 mg, 2.28 mmol) and DIEA (80 mg, 0.62 mmol) and the reaction mixture was stirred for an additional 6 h. At this point the reaction mixture was filtered and the filtrate added to 150 mL of ether. The tan precipitate was collected in air (1.02 g, 1.35 mmol; 98%) and carried on to 186 mg (1.04 mmol; 75% overall yield) of 4-(3-oxobutyl)-4-methyl-2,5-cyclohexadien-1-one.

4-(3-Oxobutyl)-4-methyl-2,5-cyclohexadien-1-one. Compound **XI** (1.0 g, 1.33 mmol) was dissolved in CH_3CN (3 g) in air and treated with 1.0 equiv of DDQ (303 mg, 1.33 mmol). The reaction mixture immediately turned deep black and was stirred for 1 min. The mixture was then dissolved in 10% $NaHCO_3$ (40 mL) and the aqueous phase extracted with ether (3 × 40 mL) and CH_2Cl_2 (1 × 40 mL). The combined pale yellow extracts were dried over anhydrous sodium sulfate. After evaporation of the solvent, a significant amount of water remained. The dienone was dissolved in CH_2Cl_2 and redried over anhydrous sodium sulfate. After evaporation of the solvent, a yellow oil (186 mg, 84%) remained which was identified by ^{1}H NMR as the crude 2,5-dienone. The crude dienone was purified by preparative TLC chromatography to give a clear oil (150 mg, 68%) which was analytically pure. R_f = 0.80 (1:1 hexanes:acetone). Overall yield from phenol: 65%. ^{1}H NMR ($CDCl_3$): δ 6.69 (d, 2H, J = 10 Hz), 6.25 (d, 2H, J = 10 Hz), 2.16 (t, 2H), 2.03 (s, 3H), 1.92 (t, 2H), 1.26 (s, 3H). ^{13}C NMR ($CDCl_3$) δ 208.2 (CO), 186.7 (CO), 155.8 (2CH), 129.7 (2CH), 41.9 (C), 39.2 (CH_2), 33.4 (CH_2), 30.6 (CH_3), 26.4 (CH_3). IR: ν_{CO} = 1653, 1718 cm^{-1}. Anal. Calcd for $C_{11}H_{14}O_2$: C, 74.13; H, 7.92. Found: C, 74.11; H, 8.06.

[Os(NH$_3$)$_5$(4α-(*trans*-3-oxo-1-butenyl)-4β-methyl-2β,3β-η^2-2,5-cyclohexadien-1-one)](OTf)$_2$ (XIII). The η^2-*p*-cresol complex **II** (100 mg, 0.147 mmol) was dissolved in CH_3CN (700 mg). 3-Butyn-2-one (9.72 mg, 0.143 mmol) was added then DIEA (1.90 mg, 0.0147 mmol) and after a few minutes, the reaction mixture turned dark red. After 15 min the reaction mixture was added directly to ether (20 mL) to yield a red precipitate (95 mg, 87%) which was collected, washed with ether, and dried *in vacuo*. ^{1}H NMR (CD_3CN): δ 6.86 (d, 1H, J = 8.0 Hz), 6.16 (d, 2H, J = 12.6 Hz), 5.70 (d, 1H, J = 8.0Hz), 4.63 (d, 1H, J = 8.0Hz), 4.52 (br s, 3H, *trans*-NH_3), 4.22 (d, 1H, J = 8.0Hz), 3.35 (br s, 12 H, *cis*-NH_3), 2.19 (s, 3H), 1.32 (s, 3H). ^{13}C NMR (CD_3CN): δ 201.2 (CO), 199.1 (CO), 153.3 (CH), 146.9 (CH), 128.9 (CH), 128.3 (CH), 57.7 (CH), 51.3 (CH), 45.0 (C), 31.6 (CH_3), 21.8 (CH_3). Cyclic voltammetry: $E_{p,a}$ = 0.95 V. Anal. Calcd for $C_{59}H_{67}O_2N_5B_2Os\cdot H_2O$: C, 63.96; H, 6.28; N, 6.32. Found: C, 63.80; H, 6.19; N, 6.20.

[Os(NH$_3$)$_5$(4α-(*N*-methylsuccinimid-3-yl)-4β-methyl-2β,3β-η^2-2,5-cyclohexadien-1-one)](OTf)$_2$ (XIV). The η^2 -*p*-cresol complex **II** (230.9 mg, 0.339 mmol) and methyl maleimide (38.0 mg, 0.342 mmol) were dissolved in CH_3CN (800 mg). After 1 min, DIEA (4.13 mg, 0.032 mmol) was added and the reaction mixture was stirred for ~1.5 h, over which time it turned deep red. The reaction mixture was then added directly to ether (20 mL) to yield a tan precipitate (215 mg, 85%) which was washed with CH_2Cl_2 and ether, then dried *in vacuo* (de > 90%). ^{1}H NMR (CD_3CN): δ 6.50 (d, 1H, J = 10 Hz), 5.83 (d, 1H, J = 10 Hz), 4.50 (br s, 3H, *trans*-NH_3), 4.18 (d, 1H, J = 8.0 Hz), 4.12 (d, 1H, J = 8.0 Hz), 3.30 (br s, 12 H, *cis*-NH_3), 3.25 (m, 1H), 2.82 (s, 3H), 2.70–2.90 (m, 2H), 1.12 (s, 3H). ^{13}C NMR (acetone-d_6): δ 198.5 (CO), 177.5 (CO), 177.3 (CO), 150.6 (CH), 131.7 (CH), 54.8 (CH), 52.6 (CH), 45.0 (CH), 40.3 (CH), 30.1 (CH_2), 28.1 (NCH_3), 24.3 (CH_3). Cyclic voltammetry: $E_{p,a}$ = 1.00 V. Anal. Calcd for $C_{60}H_{68}O_3N_6B_2Os$: C, 63.60; H, 6.05; N, 7.42. Found: C, 63.50; H, 5.65; N, 7.34.

[Os(NH$_3$)$_5$(6α-(*N*-methylsuccinimid-3-yl)-4β-methyl-2β,3β-η^2-2,4-cyclohexadien-1-one)](OTf)$_2$ (XV). The η^2 -*p*- cresol complex **II** (81.0 mg, 0.119 mmol), methyl maleimide (12.0 mg, 0.108 mmol) and zinc triflate (43.0mg, 0.118 mmol) were dissolved in CH_3CN (800 mg) After 1 min, DIEA (12.0 mg, 0.093 mmol) was added and the reaction mixture was stirred 6 h upon which it darkened considerably. The reaction mixture was then added directly to stirring ether (100 mL) to yield a tan precipitate. The crude solid was redissolved in acetone (1 g) and this solution was added to ether (100 mL) to give a light tan precipitate (88 mg, 93.4%) which was washed with CH_2Cl_2, ether, and dried *in vacuo*. ^{1}H NMR (CD_3CN): δ 5.18 (s, 1H), 4.84 (d, 1H, J = 6.6Hz), 4.60 (br s, 3H, *trans*-NH_3), 4.37 (d, 1H, J = 6.6 Hz), 3.85 (m, 1H), 3.31 (br s, 12 H, *cis*-NH_3), 3.21 (m, 1H), 2.86 (s, 3H), 2.60 (m, 2H), 1.87 (s, 3H). ^{13}C NMR (CD_3CN): δ 213.2 (CO), 179.2 (CO), 176.9 (CO), 142.5 (CH), 115.1 (CH), 53.7 (CH), 50.5 (CH), 47.7 (CH), 43.0 (CH), 30.8 (CH_2), 26.0 (NCH_3), 25.0 (CH_3). Cyclic voltammetry: $E_{p,a}$ = 0.82 V. Anal. Calcd for $C_{60}H_{68}O_3N_6B_2Os\cdot 2H_2O$: C, 61.64; H, 6.21; N, 7.19. Found: C, 61.75; H, 6.15; N, 6.88.

[Os(NH$_3$)$_5$(η^2-5,6,7,8-tetrahydro-2-naphthol)](OTf)$_2$ (XVI). A solution of $Os(NH_3)_5(OTf)_3$ (488 mg, 0.676 mmol) in DMAc (1.50 g) was treated with a solution of 5,6,7,8-tetrahydronaphthol (1.96 g, 13.2 mmol) in DME (3.3 g). Freshly activated magnesium powder (1.25 g) was immediately added, and the reaction was monitored by cyclic voltammetry. After 30 min the reaction mixture was added to ether (300 mL). A dark red oil formed which, after decanting excess ether, was redissolved in acetone and added to CH_2Cl_2 (200 mL). A light tan precipitate (394 mg, 84%) was collected, washed with ether, and dried *in vacuo*. ^{1}H NMR integretation revealed a 3:2 ratio of η^2-arene:η^2-2,4-dienone tautomers. Characterization data are reported for the η^2-arene form. ^{1}H NMR (CD_3CN): δ 7.80 (br s, 1H), 5.38 (s, 1H), 5.01 (d, 1H, J = 7.2Hz), 4.86 (d, 1H, J = 7.2Hz), 4.08 (br s, 3H, *trans*-NH_3), 2.98 (br s, 12 H, *cis*-NH_3), 1.50–2.60 (m, 8H). ^{13}C NMR (CD_3CN): δ 164.2 (C), 130.4 (C), 124.8 (C), 99.2 (CH), 65.8 (CH), 56.7 (CH), 31.6 (CH_2), 30.7 (CH_2), 24.1 (CH_2), 23.4 (CH_2). Cyclic voltammetry: $E_{p,a}$ = 0.35 V. Anal. Calcd for $C_{58}H_{67}ON_5B_2Os\cdot H_2O$: C, 64.50; H, 6.44; N, 6.48. Found: C, 64.87; H, 6.15; N, 6.72.

[Os(NH$_3$)$_5$(5,6,7,8-tetrahydro-1α-(3-oxobutyl)-η^2-2β(1*H*)-naphthalen-2-one)](OTf)$_2$ (XVII). The η^2-5,6,7,8-tetrahydro-2-naphthol complex **XVI** (60.3 mg, 0.083 mmol) and $ZnOTf_2$ (33.0 mg, 0.091 mmol) were dissolved in CH_3CN (800 mg) to form a dark orange solution. DIEA (11.0 mg, 0.095 mmol) then MVK (5.55 mg, 0.079 mmol) were added, and the reaction mixture was stirred for 22 h before direct addition to ether (20 mL). An oily solid formed which was redissolved in acetone (1 g) and added directly to ether (20 mL). A tan precipitate formed (55 mg, 84%) which was collected, washed with ether, and dried *in vacuo*. **XVII** was isolated exclusively in its 2,4-dienone form. ^{1}H NMR (CD_3CN): δ 4.66 (d, 1H, J = 8.0Hz), 4.47 (br s, 3H, *trans*-NH_3), 4.46 (d, 1H, J = 8.0Hz), 3.32 (br s, 12 H, *cis*-NH_3), 2.06 (s, 3H), 1.25–2.60 (m, 13H). ^{13}C NMR (CD_3CN): δ 216.4 (CO), 209.1 (CO), 135.6 (C), 127.6 (C), 54.4 (CH), 51.3 (CH), 50.6 (CH), 38.3 (CH_2), 30.9 (CH_2), 29.7 (CH_3), 25.3 (CH_2), 23.4 (CH_2), 23.2 (CH_2), 22.8 (CH_2). Cyclic voltammetry: $E_{p,a}$ = 0.78 V. Anal. Calcd for $C_{62}H_{73}O_2N_5B_2Os\cdot 1.5H_2O$: C, 64.24; H, 6.61; N, 6.04. Found: C, 64.31; H, 6.31; N, 5.85.

1-(3-Oxobutyl)-5,6,7,8-tetrahydro-2-naphthol. Compound **XVII** (135 mg, 0.171 mmol) was dissolved in CH_3CN (2.5 g) and was treated with AgOTf (43.7 mg, 0.308 mmol). The reaction mixture immediately turned deep red and was stirred for 1 h, after which H_2O (20 mL) was added. The aqueous solution was extracted with ether (2 × 25 mL) and CH_2Cl_2 (2 × 25 mL). The combined extracts were dried over anhydrous magnesium sulfate. Removal of the solvent by rotary evaporation gave a pale yellow oil. The crude product was purified by silica chromatography with ether as the eluant. R_f = 0.60. A clear oil (20 mg, 54%) was obtained after evaporation. ^{1}H NMR ($CDCl_3$): δ 6.95 (d, 1H, J = 8.1 Hz), 6.66 (d, 1H, J = 8.1 Hz), 5.40 (br s, 1H), 1.70–2.80 (m, 12H), 1.67 (s, 3H). ^{13}C NMR ($CDCl_3$): δ 150.5 (C), 135.9 (C), 129.0 (C), 128.4 (CH), 120.0 (C), 115.0 (CH), 96.0 (C), 31.9 (CH_2), 29.9 (CH_2), 28.9 (CH_2), 26.7 (CH_2), 23.6 (CH_2), 23.4 (CH_2), 19.5 (CH_3). Anal. Calcd for $C_{14}H_{18}O_2$: C, 77.03; H, 8.31. Found: C, 76.77; H, 8.07.

[Os(NH$_3$)$_5$ (5,6,7,8-tetrahydro-4aα-(3-oxobutyl)-η^2-2β,3β(4a*H*)-naphthalen-2-one)](OTf)$_2$ (XVIII). The η^2-5,6,7,8-tetrahydro-2-naphthol complex **XVI** (330 mg, 0.457 mmol) was dissolved in CH_3CN (1.50 g). This solution was treated with MVK (31.2 mg, 0.446 mmol) and cooled to –40 °C. After 15 min, DIEA (16.7 mg, 0.129 mmol) was added and the reaction mixture was allowed to sit for 24 h at –40 °C, then added directly to ether (100 mL). A tan precipitate formed (310 mg, 85.7%) which was collected, washed with ether, and dried *in vacuo*. ^{1}H NMR

(CD_3CN): δ 5.68 (s 1H), 4.38 (br s, 3H, *trans*-NH_3), 4.27 (d, 1H, J = 7.5 Hz), 4.18 (d, 1H, J = 7.5 Hz), 3.26 (br s, 12 H, *cis*-NH_3), 1.60–2.60 (m, 10H), 2.06 (s, 3H), 1.10–1.30 (m, 2H). ^{13}C NMR (CD_3CN): δ 209.0 (CO), 199.2 (CO), 166.2 (C), 126.8 (CH), 59.9 (CH), 53.5 (CH), 45.5 (C), 38.3 (CH_2), 36.9 (CH_2), 34.4 (CH_2), 32.7 (CH_2), 29.8 (CH_3), 26.7 (CH_2), 21.6 (CH_2). Cyclic voltammetry: $E_{p,a}$ = 0.93 V. IR: ν_{CO} = 1628, 1701 cm^{-1}. Anal. Calcd for $C_{62}H_{73}O_2N_5B_2Os \cdot 1.5H_2O$: C, 64.24; H, 6.61; N, 6.04. Found: C, 64.17; H, 6.68; N, 6.41.

(5,6,7,8-Tetrahydro-4a-(3-oxobutyl)-(4a*H*)-naphthalen-2-one). Compound **XVIII** (135 mg, 0.303 mmol) was dissolved in CH_3CN (3.0 g) and treated with 1 equiv of DDQ (70.0 mg, 0.308 mmol). The reaction mixture immediately turned black and was stirred for 1 min. The mixture was then diluted to 40 mL with 10% $NaHCO_3$. The dienone was extracted with anhydrous ether (3 × 40 mL) and CH_2Cl_2 (1 × 40 mL). The combined pale yellow extracts were dried over anhydrous sodium sulfate. After removal of the solvent by rotary evaporation a significant amount of water remained. The dienone was dissolved in CH_2Cl_2 (20 mL) and redried over anhydrous sodium sulfate. Removal of the solvent by rotary evaporation gave pure 5,6,7,8-tetrahydro-4a-(3-oxobutyl)-(4a*H*)-naphthalen-2-one as a pale yellow oil (59.6 mg, 85%). ^1H NMR ($CDCl_3$): δ 6.60 (d, 1H, J = 9.6 Hz), 6.25 (d, 1H, J = 9.6 Hz), 6.16 (s, 1H), 2.02 (s, 3H), 1.60–2.20 (m, 7H), 1.20–1.40 (m, 5H). ^{13}C NMR ($CDCl_3$): δ 208.1 (CO), 187.6 (CO), 166.4 (C), 156.2 (CH), 129.3 (CH), 126.8 (CH), 44.7 (C), 39.2 (CH_2), 38.6 (CH_2), 33.1 (CH_2), 29.7 (CH_3), 28.8 (CH_2), 28.4 (CH_2), 21.0 (CH_2). Anal. Calcd for $C_{14}H_{18}O_2 \cdot 0.67H_2O$: C, 73.02; H, 8.46. Found: C, 73.01; H, 8.46.

[Os(NH_3)$_5$(5,6,7,8-tetrahydro-4aα-(*trans*-3-oxo-1-butenyl)-η²-2β-(4a*H*)-naphthalen-2-one)](OTf)$_2$ (XIX). The η²-5,6,7,8-tetrahydro-2-naphthol complex **XVI** (49.7 mg, 0.069 mmol) was dissolved in CH_3CN (700 mg). This solution was treated with 3-butyn-2-one (4.69 mg, 0.069 mmol) then DIEA (0.756 mg, 0.0059 mmol). After a few minutes, the reaction mixture turned dark red and, after ~20 min, was added directly to ether (20 mL) to yield a red precipitate (51 mg, 93.8%) which was collected, washed with ether, and dried *in vacuo*. ^1H NMR (CD_3CN): δ 6.62 (d, 1H, J = 13.0Hz), 6.20 (d, 1H, J = 13.0Hz), 5.65 (s, 1H), 4.79 (d, 1H, J = 8.0Hz), 4.42 (br s, 3H, *trans*-NH_3), 4.13 (d, 1H, J = 8.0Hz), 3.31 (br s, 12 H, *cis*-NH_3), 2.21 (s, 3H), 0.80–2.80 (m, 8H). ^{13}C NMR (CD_3CN): δ 201.4 (CO), 199.1 (CO), 165.2 (C), 147.9 (CH), 129.6 (CH), 126.5 (CH), 57.3 (CH), 51.0 (CH), 48.8 (C), 35.5 (CH_2), 34.1 (CH_2), 31.6 (CH_3), 27.0 (CH_2), 23.3 (CH_2). Cyclic voltammetry: $E_{p,a}$ = 0.94 V. Anal. Calcd for $C_{62}H_{71}O_2N_5B_2Os \cdot 2H_2O$: C, 63.86; H, 6.48; N, 6.01. Found: C, 63.77; H, 6.57; N, 6.17.

[Os(NH_3)$_5$(6-(2-butylidene)-η²-2β,3β-2,4-cyclohexadiene-1-one)](OTf)$_2$ (XXIV). The η²-phenol complex I (112 mg, 0.168 mmol) was dissolved in CH_3CN (900 mg), and excess crotonaldehyde (67.0 mg, 0.955 mmol) was added. The reaction mixture was stirred for 24 h, after which it was added directly to ether (20 mL) to give a light green precipitate (95 mg, 85.2%). ^1H NMR (CD_3CN): δ 7.22 (d, 1H, J = 7.2 Hz), 6.74 (d, 1H, J = 5.4 Hz), 6.60 (m, 1H), 6.55 (t, 1H), 6.48 (m, 1H), 5.37 (t, 1H), 4.89 (d, 1H, J = 6.3 Hz), 4.67 (br s, 3H, *trans*-NH_3), 3.32 (br s, 12 H, *cis*-NH_3), 1.70 (d, 3H). ^{13}C NMR (CD_3CN): δ 200.7 (CO), 140.3 (CH), 133.9 (CH), 132.2 (CH), 130.3 (CH), 129.4 (CH), 117.2 (C), 53.7 (CH), 52.0 (CH), 19.4 (CH_3). Cyclic voltammetry: $E_{p,a}$ = 1.00 V. Anal. Calcd for $C_{58}H_{64}ON_5B_2Os \cdot H_2O$: C, 64.68; H, 6.18; N, 6.50. Found: C, 64.44; H, 6.45; N, 6.72.

[Os(NH_3)$_5$(4β-methyl-6-(2-butylidene)-η²-2β,3β-2,4-cyclohexadiene-1-one)](OTf)$_2$ (XXV). The η²-*p*-cresol complex II (100 mg, 0.147 mmol) was dissolved in CH_3CN (900 mg) to form a dark orange solution. Crotonaldehyde (20 mg, 0.289 mmol) then pyridine (10 mg, 0.126 mmol) were added. The reaction mixture turned dark green and was stirred for 26 h before direct addition to ether (20 mL). A green solid (70 mg, 65%) was collected, washed with ether, and dried *in vacuo*. ^1H NMR (DMSO-d_6): δ 6.97 (d, 1H, J = 12.0 Hz), 6.57 (d of d, 1H, J = 12.0, 14.7 Hz), 6.40 (s 1H), 6.26 (m, 1H), 5.02 (d, 1H, J = 6.9 Hz), 4.93 (br s, 3H, *trans*-NH_3), 4.86 (d, 1H, J = 6.9 Hz), 3.54 (br s, 12 H, *cis*-NH_3), 2.02 (s, 3H), 1.62 (d, 3H). ^{13}C NMR (DMSO-d_6): δ 199.5 (CO), 145.5 (CH), 136.7 (CH), 133.5 (CH), 130.3 (CH), 125.1 (C), 113.6 (C), 53.8 (CH), 53.4 (CH), 24.7 (CH_3), 20.3 (CH_3). Cyclic voltammetry: $E_{p,a}$ = 0.99 V. Anal. Calcd for $C_{59}H_{68}ON_5B_2Os \cdot 2.5H_2O$: C, 63.38; H, 6.40; N, 6.26. Found: C, 63.02; H, 6.59; N, 6.62.

[Os(NH_3)$_5$(4-methoxy-2,3-η²-phenol)](OTf)$_2$ (XXVI). A solution of $Os(NH_3)_5(OTf)_3$ (525 mg, 0.727 mmol) in DMAc (1.50 g) was treated with an excess of 4-methoxyphenol (1.88 g, 15.1 mmol) in DME (3.3 g). Freshly activated magnesium powder (1.25 g) was immediately added. After 0.5 h the reaction mixture was added to CH_2Cl_2 (300 mL). A dark orange precipitate formed (430 mg, 84.8%) which was collected, washed with ether, and dried *in vacuo*. ^1H NMR integration revealed a 1:1 ratio of η²-arene:η²-2,4-dienone tautomers. Characterization data are reported for the η²-arene tautomer. ^1H NMR (CD_3CN): δ 8.30 (br s, 1H), 5.47 (d, 1H, J = 8.1Hz), 5.37 (d, 1H, J = 8.1Hz), 4.93 (s, 2H), 4.10 (br s, 3H, *trans*-NH_3), 3.55 (s, 3H, OCH_3), 2.96 (br s, 12 H, *cis*-NH_3). Cyclic voltammetry: $E_{p,a}$ = 0.53. Anal. Calcd for $C_{55}H_{63}O_2N_5B_2Os$: C, 63.64; H, 6.12; N, 6.75. Found: C, 63.98; H, 6.47; N, 6.61.

[Os(NH_3)$_5$(6α,6β-bis(3-oxobutyl)-4β-methoxy-2β,3β-η²-2,4-cyclohexadien-1-one)](OTf)$_2$ (XXIX). The η²-4-methoxyphenol complex **XXVI** (258 mg, 0.371 mmol) was dissolved in CH_3OH (1.50 g). This solution was treated with MVK (134 mg, 1.91 mmol), then DIEA (49.0 mg, 0.381 mmol) was added, and the reaction mixture was stirred for 20 min before being added to ether (100 mL). A tan precipitate formed (260 mg, 83.8%) which was collected, washed with ether, and dried *in vacuo*. ^1H NMR (CD_3CN): δ 6.23 (s, 1H), 4.60 (br s, 3H, *trans*-NH_3), 4.56 (d, 1H, J = 8.1 Hz), 4.40 (d, 1H, J = 8.1 Hz), 3.56 (s, 3H, OCH_3), 3.30 (br s, 12 H, *cis*-NH_3), 2.07 (s, 3H), 2.06 (s, 3H), 1.45–2.70 (m, 8H). ^{13}C NMR (CD_3CN): δ 219.6 (CO), 210.5 (CO), 208.9 (CO), 158.7 (C), 95.9 (CH), 50.1 (C), 47.8 (CH), 46.2 (CH), 38.7 (CH_2), 38.0 (CH_2), 35.1 (CH_2), 29.6 (CH_3), 29.5 (CH_3), 28.6 (CH_2). Cyclic voltammetry: $E_{p,a}$ = 0.88 V.

(6,6-Bis(3-oxobutyl)-4-methoxy-2,4-cyclohexadien-1-one). Compound **XXIX** (220 mg, 0.263 mmol) was dissolved in CH_3CN (2.0 g) and treated with 1 equiv of DDQ (60.0 mg, 0.263 mmol). The reaction mixture immediately turned black and was stirred for 0.5 h. The mixture was then diluted to 40 mL with 10% $NaHCO_3$. The dienone was extracted with anhydrous ether (3 × 40 mL) and CH_2Cl_2 (1 × 40 mL). The combined extracts were dried over anhydrous sodium sulfate. After removal of the solvent by rotary evaporation, a significant amount of water remained. The dienone was dissolved in CH_2Cl_2 (20 mL) and redried over anhydrous sodium sulfate. Removal of the solvent by rotary evaporation gave the pure dienone 6,6-bis(3-oxobutyl)-4-methoxy-2,4-cyclohexadien-1-one as a clear oil (50.0 mg, 71.8%). ^1H NMR ($CDCl_3$): δ 6.96 (d, 1H, J = 10.2 Hz), 6.10 (d, 1H, J = 10.2 Hz), 4.95 (d, 1H, J = 1.0 Hz), 3.61 (s, 3H), 2.08 (s, 6H), 1.80–2.25 (m, 8H). ^{13}C NMR ($CDCl_3$): δ 208.3 (2CO), 205.2 (CO), 152.0 (C), 143.0 (CH), 128.4 (CH), 109.8 (CH), 55.5 (OCH_3), 52.6 (C), 38.9 ($2CH_2$), 35.3 ($2CH_2$), 30.4 ($2CH_3$). Anal. Calcd for $C_{15}H_{20}O_4$: C, 68.16; H, 7.63. Found: C, 68.13; H, 8.05.

[Os(NH_3)$_5$(4α,6-bis(3-oxobutyl)-4β-methyl-η²-2β,3β-2,5-cyclohexadien-1-one)](OTf)$_2$ (XXX). The η²-*p*-cresol complex **II** (228.4 mg, 0.335 mmol) and zinc triflate (142 mg, 0.391 mmol) were dissolved in CH_3CN (1.5 g). MVK (48 mg, 0.684 mmol) then DIEA (10.0 mg, 0.0775 mmol, 0.23 equiv) were added, and the reaction mixture was stirred for 2 h, over which time it darkened. The mixture was then added to CH_2Cl_2 (300 mL), and a pale orange solid formed. Reprecipitation from acetone/ether gave a light orange solid (210 mg, 74.5%). ^1H NMR (CD_3CN): δ 6.23 (s, 1H), 4.39 (br s, 3H, *trans*-NH_3), 4.28 (d, 1H, J = 7.5 Hz), 4.17 (d, 1H, J = 7.5 Hz), 3.25 (br s, 12 H, *cis*-NH_3), 2.10–2.60 (m, 6H), 2.05 (s, 3H), 2.04 (s, 3H), 1.80-2.00 (m, 2H), 1.11 (s, 3H). ^{13}C NMR (CD_3CN): δ 209.8 (CO), 209.4 (CO), 199.3 (CO), 150.7 (CH), 137.9 (C), 57.8 (CH), 53.1 (CH), 42.3 (C), 41.8 (CH_2), 39.3 (CH_2), 38.2 (CH_2), 29.7 (CH_3), 29.5 (CH_3), 24.2 (CH_3), 23.5 (CH_2). Cyclic voltammetry: $E_{p,a}$ = 0.95 V.

Results

The compound [Os(NH_3)$_5$(2,3-η²-phenol)](OTf)$_2$ (I) is prepared by the one-electron reduction (Zn^0 or Mg^0) of the osmium(III) precursor $Os(NH_3)_5(OTf)_3$ in the presence of an excess of the corresponding arene.[7] When an acetonitrile solution of I is treated with 1.0 equiv of methyl vinyl ketone, the solution becomes deep red. Upon addition to ether, a tan salt is obtained (**IV**) whose ^1H and ^{13}C NMR data show four olefinic doublets over the range 3.8 to 6.6 ppm and a ^{13}C carbonyl resonance at 199.9 ppm, features which indicate the formation of a 2,5-cyclohexadien-1-one isomer.[7] In addition, two sets of methylene, a methyl, and a second carbonyl resonance (209 ppm) are diagnostic for the 3-oxobutyl group. Infrared data show two carbonyl groups with corresponding C=O stretching frequencies of 1636 and 1701 cm^{-1}. A cyclic voltammogram of this compound indicates a reversible one-electron oxidation at 0.93 V, characteristic of a pentaammineosmium(II) complex of an electron-deficient olefin.[7] Taken together these data are consistent with

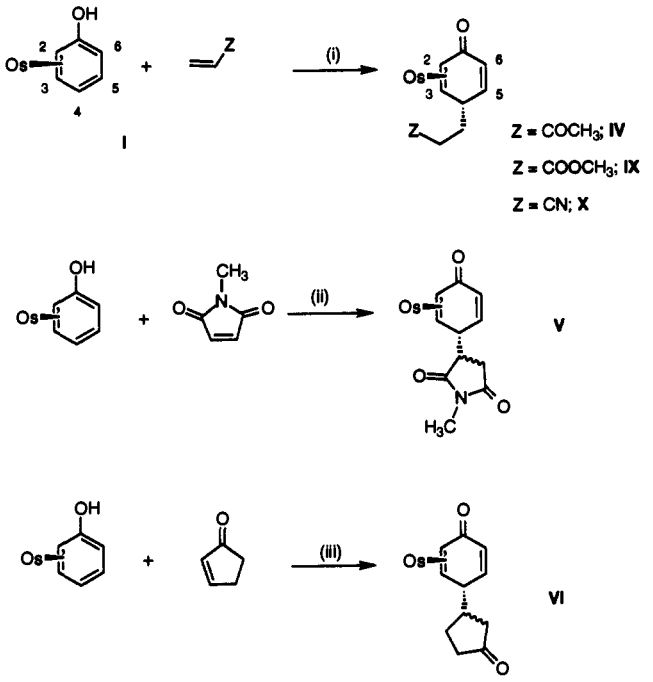


Figure 1. Conjugate addition reactions with the η^2-phenol complex **I** and various Michael acceptors: (i) **IV**, MVK/pyridine/CH_3CN; **IX**, methyl acrylate/ $Zn(OTf)_2$/DIEA/CH_3CN; **IX**, acrylonitrile/$Zn(OTf)_2$/DIEA/ CH_3CN. (ii) *N*-methylmaleimide/pyridine/CH_3CN. (iii) 2-cyclopenten-1-one/pyridine/CH_3CN.

a single diastereomer (de > 90%) of a 4-alkylated 2,5-cyclohexadien-1-one complex, the C(4) conjugate addition product of the electrophile and metalated phenol (Figure 1). The absence of coupling between H(3) and H(4) and a substantial NOE between H(4) and the *cis*-ammine protons indicate that conjugate addition occurs to the α face of the phenol ring, opposite to that of metal coordination (Figure 1).[12]

Scope of Reaction: Variation of Michael Acceptors. By a method similar to that described for the formation of **IV**, the η^2-phenol complex I undergoes a conjugate addition reaction at C(4) with a variety of Michael acceptors (Figure 1) including those with β-substitution. In most cases, the addition reaction is most conveniently carried out with an amine base as the catalyst.[13] For example, when *N*-methylmaleimide or 2-cyclopenten-1-one is combined with the phenol complex I along with ~1 equiv of pyridine, *N*,*N*-dimethylaniline, or 2,6-lutidine, the corresponding dienones (**V** and **VI**) are generated as single diastereomers (de > 90%).[14]

Less reactive electrophiles such as methyl acrylate or acrylonitrile fail to undergo conjugate addition with the phenol complex I in the presence of base alone. However, in the presence of a Lewis acid cocatalyst, conjugate addition may be accomplished in good yield. For methyl acrylate and acrylonitrile, the best results have been achieved when $Zn(OTf)_2$ (0.5–1.0 equiv) is added to the reaction mixture *in addition to DIEA*. Conjugate addition proceeds smoothly at C(4) to yield the corresponding dienone ester **IX** or nitrile **X**, respectively (Figure 1). Surprisingly, these reactions fail when Zn^{2+} alone is added as the catalyst (*vide infra*).[15]

In order to optimize the zinc-promoted conjugate addition for less-activated Michael acceptors, a series of experiments was carried out on the reactions of methyl acrylate and acrylonitrile with the η^2-phenol complex I. These results are summarized in Table 1. In the first series of experiments (entries 1–11), the initial concentrations of methyl acrylate and I are fixed at 0.15 M, while the initial concentrations of base and of Zn^{2+} are varied. With 1 equiv each of Zn^{2+} and DIEA (0.15 M), the reaction shows a half-life of 6 h at 22 °C. This half-life is directly proportional to the concentration of base (entries 1,6, and 7) but independent of $[Zn^{2+}]$ (entries 1–4) provided that the amount of Zn^{2+} was kept at 0.5 equiv or higher. At lower concentrations of the zinc, the reaction does not proceed. Substituting Proton Sponge, pyridine, or DBU for DIEA also retards the reaction (entries 8–10). Using 1 equiv of base, only the DBU reaction was rapid enough ($t_{1/2}$ < 12 h) to overcome substitution of the arene by solvent. Conjugate addition does occur to a limited extent (20%) when Zn^{2+} is added without base, but the major product recovered is an unidentified osmium complex that, judging from NMR data,[16] does not contain the electrophile fragment. When this series of reactions is repeated for acrylonitrile (entries 12–18), virtually identical results are obtained except that the reaction rate is moderately faster than for the ester.

Surprisingly, the α-substituted Michael acceptor 3-methyl-3-butene-2-one, is sufficiently sluggish to react with I that arene substitution by the solvent preempts any ligand-centered reaction, even in large excess of the amine base. In this case, $BF_3{\cdot}OEt_2$ sucessfully catalyzes the reaction.[17] However, the β,β-disubsti-

Table 1. Various Reaction Conditions and Approximate Half-lives for the Reaction of the η^2-Phenol Complex I with Several Michael Acceptors (Electrophiles) ($[Os]^0 = [Acceptor]^0 = 0.15$ M)

run no.	electrophile	base	amt of base (equiv)	Zn-$(OTf)_2$	half-life (h)
1	methyl acrylate	DIEA	1.0	1.0	6
2	methyl acrylate	DIEA	1.0	0.5	6
3	methyl acrylate	DIEA	1.0	2.0	6
4	methyl acrylate	DIEA	1.0	0.2	NR[b]
5	methyl acrylate	DIEA	1.0	0.0	NR[b]
6	methyl acrylate	DIEA	0.2	1.0	>24[a]
7	methyl acrylate	DIEA	6.0	1.0	1
8	methyl acrylate	pyridine	1.0	1.0	NR
9	nethyl acrylate	Proton Sponge	1.0	1.0	NR[b]
10	methyl acrylate	DBU	1.0	1.0	13
11	methyl acrylate	(none)		1.0	>24[a]
12	acrylonitrile	DIEA	1.0	1.0	2
13	acrylonitrile	DIEA	1.0	0.5	2
14	acrylonitrile	DIEA	2.0	1.0	1
15	acrylonitrile	DIEA	4.0	1.0	0.5
16	acrylonitrile	DIEA	1.0	0.2	NR[b]
17	acrylonitrile	DIEA	0.2	1.0	>24[a]
18	acrylonitrile	DBU	1.0	1.0	3.5
19	MVK	DIEA	0.0	0.0	0.2
20	MVK	DIEA	1.0	0.0	<0.1
21	MVK	DIEA	0.0	1.0	<0.1

[a] Unidentified side product formed. [b] Solvent substitution product formed.

(12) With the exception of the steroid system, the metal is depicted as being β-coordinated. Compounds **V** and **X** had 8% and 17% NOE enhancements, respectively, between H(4) and the corresponding *cis*-ammine.

(13) Many of these reactions may be carried out in absence of base, but reaction times are considerably longer.

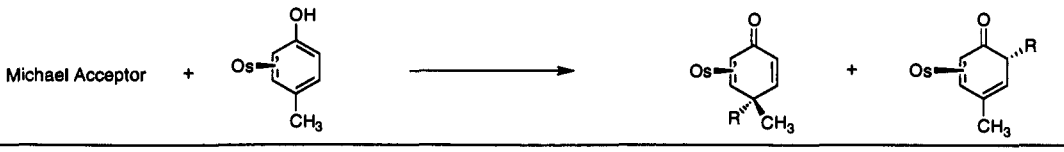
(14) Using a stronger base such as DIEA partially induces a tautomerization of the dienone ligand to its phenolic form at 20 °C, although this side reaction is eliminated at reduced temperature (–35 °C) or short reaction times (< 5 min).

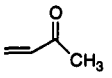
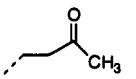
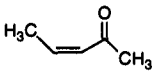
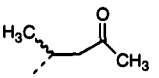
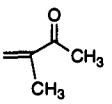
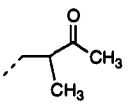
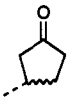
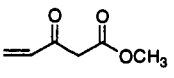
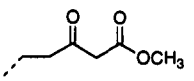
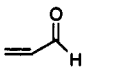
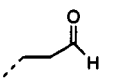
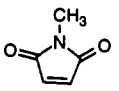
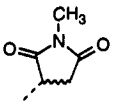
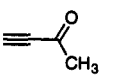
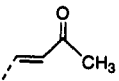
(15) In the case of the acrylate ester, conjugate addition at C(4) can be accomplished in the absence of base using the stronger Lewis acid $BF_3{\cdot}OEt_2$, but this reaction delivers only modest yields (10–20%) of product **IX**.

(16) ^1H NMR data of the unknown Zn/Os species (300 MHz, CD_3CN): δ 7.45 (m, 1H), 7.35 (m, 1H), 5.50 (m, 1H), 5.15 (br s, 3H, *trans*-NH_3), 4.60 (m, 1H), 4.45 (m, 1H), 3.85 (br s, 12H, *cis*-NH_3). The downfield chemical shifts of the *cis*- and *trans*-ammines of this unknown species suggest that it may be a η^2-4*H*-phenolium species. This unknown osmium species is formed when less than a stoichiometric amount of base is added to the reaction mixture.

(17) Although the use of stronger bases such as $LiN(i\text{-}Pr)_2$ result in decomposition of the pentaammineosmium(II) moiety, when $BF_3{\cdot}OEt_2$ is substituted as the catalyst at –35 °C, the α-substituted olefin is also observed to undergo conjugate addition at C(4) to give a 1:1 mixture of isomers at the side chain stereocenter. Crude yield = 85%. ^1H NMR (CD_3CN, diastereomer A): δ 6.78 (d, 1H, J = 9.6 Hz), 5.86 (d, 1H, J = 9.6 Hz), 4.40 (br s, 3H, *trans*-NH_3), 4.25 (m, 1H), 4.09 (m, 1H), 3.10 (br s, 12 H, *cis*-NH_3), 1.60–2.60 (m, 4H), 1.15 (d, 3H). ^1H NMR (CD_3CN/diastereomer B): δ 6.76 (d, 1H, J = 9.6 Hz), 5.83 (d, 1H, J = 9.6 Hz), 4.40 (br s, 3H, *trans*-NH_3), 4.25 (m, 1H), 4.09 (m, 1H), 3.10 (br s, 12 H, *cis*-NH_3), 1.60–2.60 (m, 4H), 1.10 (d, 3H).

Table 2. Summary of Conjugate Addition Reactions for the η^2-*p*-Cresol Complex II with Various Michael Acceptors and Reaction Conditions[a]



Michael Acceptor	Reaction Conditions				Addition product				
	Solvent	Base	Lewis Acid	T(°C)	R	*para* (%)	*ortho* (%)	other	Run #
	CH_3CN	DIEA	–	-40		100 (XI)	0 (XII)		1
	CH_3CN	DIEA	–	25		75	0	25[a]	2
	CH_3CN	–	BF_3	-40		100	0		3
	CH_3CN	DIEA	Zn^{2+}	25		5	85	10[a]	4
	CH_3OH	DIEA	Zn^{2+}	25		100	0		5
	DME[c]	DIEA	--	25		75	25		6
	CH_3CN	–	BF_3	-40		0	100		7
	CH_3CN	DIEA	--	25		(NR)			8
	CH_3CN	--	BF_3	-40		0	100		9
	CH_3CN	DIEA	--	25		(NR)			10
	CH_3CN	DIEA	--	-40		100	0		11
	CH_3CN	DIEA	--	-40		100	0		12
	CH_3CN	DIEA	--	25		75	10	15[b]	13
	CH_3CN	DIEA	--	-40		95 (XIV)	5 (XV)		14
	CH_3CN	DIEA	Zn^{2+}	25		0	100		15
	CH_3CN	DBU	--	25		70	0	30[a]	16
	CH_3CN	PS	--	25		50	25	25[a]	17
	CH_3CN	--	–	25		85[b]	5	10[a]	18
	CH_3CN	R_2NPh	--	25		80	5	15[a]	19
	CH_3OH	PS	--	25		75	0	25[a]	20
	CH_3CN	DIEA	--	25		100 (XIII)	0		21
	CH_3OH	DIEA	--	25		100	0		22

[a] Reported yields are based on ^1H NMR data and are estimated to be accurate to within 3%. (a) *o,p*-double-alkylation product analogous to **XXX**. (b) *o*-quinone methide complex analogous to **XXV**.

tuted olefin 3-methylcyclohexenone fails to react with I under any conditions tried. Finally, we note that a Michael adduct resulting from conjugate addition at C(6) was not observed in our study for any reaction involving the phenol complex I.

Variation of Phenols. Phenols with alkyl substituents also form complexes with pentaammineosmium(II).[7] Although these compounds have ligand substitution half-lives which are somewhat shorter than that of the parent complex I, in many cases, they are sufficiently stable so that a Michael addition may be achieved, and a summary of these results may be found in Table 2 (entries 1–22). For example, when the *p*-cresol complex II is treated with 1.0 equiv of MVK in acetonitrile-d_3, ^1H NMR shows the

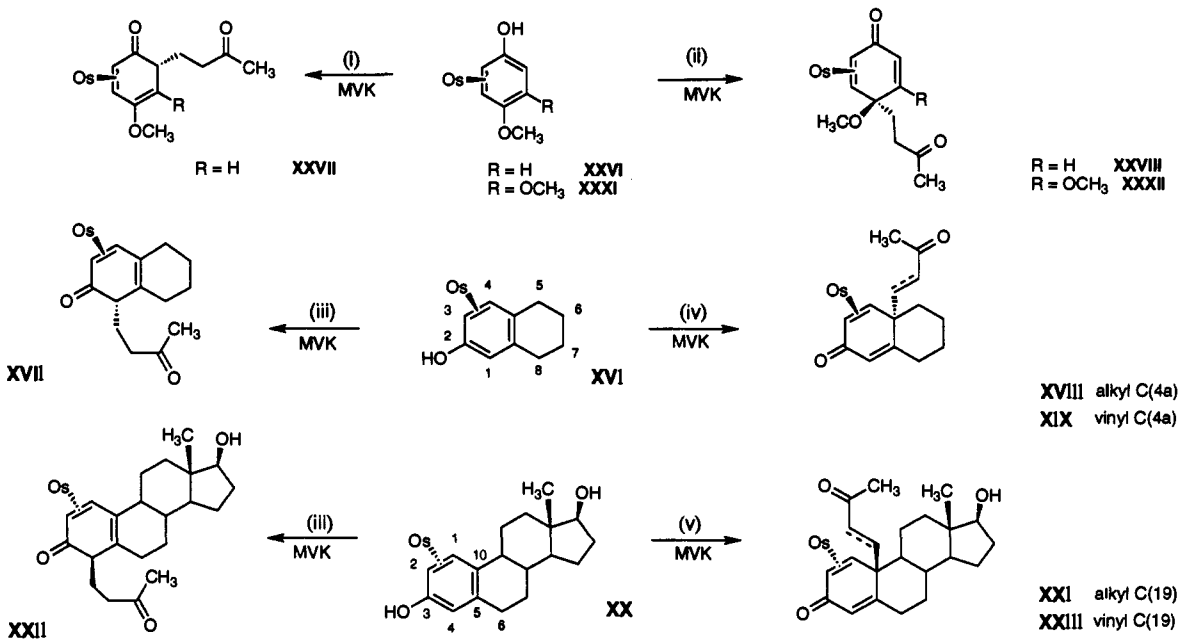


Figure 2. Osmium-promoted conjugate addition reactions with MVK and various para-substituted phenols: (i) CH_3OH/DIEA. (ii) **XXVIII**, CH_3CN/DIEA/–35 °C (yield = 10%); **XXXII**, CH_3CN/ pyridine. (iii) $CH_3CN/Zn(OTf)_2$/DIEA. (iv) CH_3CN/DIEA/–40 °C. (v) **XXI**, MVK/CH_3CN/–40 °C; **XXIII**, 3-butyn-2-one/CH_3CN/–40 °C.

appearance of two products in a ratio of 3:1 (Table 2). The major component, **XI**, which can be prepared in quantitative yield if the reaction is repeated at –35 °C, shows ^1H and ^{13}C data consistent with the formation of a 4,4-disubstituted 2,5-cyclohexadien-1-one species (**XI**), the product of a single alkylation at C(4). NOE data for **XI** show the close proximity of the methyl group to the *cis*-ammines, indicating that the addition occurs *anti* to the metal. The minor product, **XXX**, which can be prepared in good yield when the reaction is carried out with an excess of electrophile, zinc triflate, and DIEA, is the result of a C(4),C(6) double alkylation as shown in Figure 4 (*vide infra*).

The *p*-cresol complex **II** also undergoes conjugate addition at C(4) with β-substituted Michael acceptors such as *N*-methylmaleimide or 2-cyclopenten-1-one (Table 2). As with the parent phenol complex, C(4) addition of *N*-methylmaleimide dominates at –40 °C (CH_3CN, entry 14) to give product **XIV** (de > 90%). However, as with MVK, when the reaction is carried out in CH_3CN at 20 °C, significant amounts (10–50%) of C(6)-alkylated or C(6),C(4)-dialkylated products also are formed (entries 16–19).[18]

Treatment of the *p*-cresol complex **II** with 3-butyn-2-one (entries 21–22) yields a 2,5-cyclohexadienone complex isolated as a single diastereomer (de > 90%). In addition to the cyclohexadienone resonances, ^1H and ^{13}C NMR data indicate the presence of a carbonyl, methyl, and *trans*-1,2-disubstituted olefin fragment (J_{HH} = 12.6 Hz), supporting the structural assignment of the enone addition product **XIII** shown in Table 2.

As with phenol, the *p*-cresol analog **II** fails to undergo conjugate addition with hindered Michael acceptors under basic conditions, but in some cases, a reaction may be induced with the Lewis acid $BF_3{\cdot}OEt_2$. For example, 3-methyl-3-butene-2-one fails to react with **II** using a base catalyst (entry 8), yet in the presence of $BF_3{\cdot}OEt_2$, addition readily occurs (–35 °C, entry 7). However, in contrast to those observed for the closely related Michael acceptor MVK,[19] spectroscopic data reveal that the exclusive product, **XI**, is a 2,4-cyclohexadien-1-one species (Table 2), the result of conjugate addition to C(6) (*vide infra*).

For some cases, addition of $Zn(OTf)_2$ also redirects the base-catalyzed conjugate addition with the *p*-cresol ligand to C(6) (Table 2, entries 4 and 15).[20] For example, the reaction of MVK or *N*-methylmaleimide with **II** gives only para addition products (**XIV** and **XI**) when the reaction is carried out at –35 °C in CH_3CN. However, when 1 equiv of Zn^{2+} is added, mostly ortho addition products are obtained (entry 4).[21] These compounds (**XV** and **XII** in Table 2) show ^1H, ^{13}C, COSY, and ^{13}C DEPT data which are consistent with 2,4-cyclohexadienone complexes of $[Os(NH_3)_5]^{2+}$ such as $[Os(NH_3)_5(2,3\text{-}\eta^2\text{-}6\text{-methyl-}2,4\text{-cyclohexadien-1-one})]^{2+}$.[7] In particular the ^{13}C resonance of **XV** at 213.2 ppm is significantly downfield to that seen for the 2,5-dienone isomer **XIV** (198.5 ppm) and is diagnostic for a 2,4-cyclohexadien-1-one species.[22]

Even in cases where the para carbon of phenols is highly congested or electronically deactivated, C(4) conjugate addition can be accomplished with monosubstituted olefins. Osmium complexes of 5,6,7,8-tetrahydro-2-naphthol (**XVI**) and β-estradiol (**XX**) may be obtained in a manner similar to that used for the simple phenols.[9] When an acetonitrile solution of the 5,6,7,8-tetrahydro-2-naphthol (**XVI**) complex is treated with 1 equiv of MVK in the presence of DIEA at room temperature (20 °C), a 1:1 mixture of ortho (**XVII**) and para (**XVIII**) addition products is isolated. As observed for the *p*-cresol complex **II**, running the reaction at –35 °C results in conjugate addition at the para position (C(4a)) exclusively.[23] Using similar conditions, the β-estradiol complex **XX**, in which the metal coordinates the α face of the A ring, can be alkylated selectively at C(10) to give compound **XXI** in good yield (Figure 2).[9] As with the other examples provided here, alkylation occurs from the ring face opposite that of coordination (Figure 2) and, in the case of the β-estradiol complex, β-alkylation at C(10) has been verified from NOESY experi-

(18) These conjugate addition reactions are typically run with a slight excess of electrophile. Restricting the amount of electrophile to exactly 1 equiv (20 °C, CH_3CN) does not eliminate the double alkylation byproduct.

(19) In the case of MVK, the addition of BF_3 dramatically accelerates the rate of addition ($t_{1/2}$ < 5 min), leading to a product (**XI**) identical to that formed under basic conditions.

(20) In contrast to what is observed for MVK or *N*-methylmaleimide, the addition of Zn^{2+} to the reaction of 3-butyne-2-one with η^2-*p*-cresol does not alter the regiochemistry of addition as only **XIII** is formed.

(21) Partial characterization of **XII** (enol form): ^1H NMR (CD_3CN) δ 6.06 (s, 1H), 4.99 (d, 1H, J = 8.1 Hz), 4.77 (δ, 1H, J = 8.1 Hz), 4.06 (brs, 3H, *trans*-NH_3), 3.00 (br s, 12H, *cis*-NH_3), 2.23 (s, 3H), 1.50 (s, 3H).

(22) When ortho addition occurs with MVK, a stable cyclic hemiketal may be formed upon rearomatization, a process catalyzed by a moderate base (e.g., DIEA).

(23) When this reaction is carried out in methanol at –40 °C, a 1:1 mixture of isomers is observed.

ments.[9] Repeating this reaction with 3-butyne-2-one generates the unsaturated (Δ^{19}) analog **XXIII**.[24] Judging from the coupling constant for the vinyl protons (J_{HH} = 12.0 Hz), the C(10) alkene fragment resides in a trans stereochemistry as was observed for the *p*-cresol-based analog **XIII**.

Similar to that observed for the *p*-cresol complex **II**, the addition of Zn^{2+} reverses the regiochemistry for the addition of MVK to the tetrahydronaphthol and estradiol ligands (Figure 2). Thus, when $Zn(OTf)_2$ is added to a reaction mixture of MVK, base, and arene complex in CH_3CN, only the ortho products **XVII** and **XXII** are obtained over the temperature range of –40 to 20° C. Both **XVII** and **XXII** may be isolated as 2,4-dienone species, even though these forms are thermodynamically unstable with respect to the arene–hemiketals.

For the arene systems 4,4′-biphenyldiol and 4-methoxyphenol, osmium(II) complexes can be prepared and conjugate additions carried out, but predominantly ortho addition products are obtained even when using the optimized conditions for para addition of other arene substrates (CH_3CN/–40 °C; 5–10% para selectivity obtained). However, when L = 3,4-dimethoxyphenol (**XXXI**), conjugate addition with MVK proceeds smoothly, para to the hydroxy group to yield the complex **XXXII** (Figure 2).[25]

Dienone complexes having a hydrogen on the sp^3-ring carbon readily equilibrate with their phenol tautomers in the presence of moderate base. Once the arene complex is reformed, a second conjugate addition may be carried out, and two examples of this are illustrated in Figure 4. In the presence of DIEA, the 2,4-dienone species **XII** readily converts to its phenolic form (in equilibrium with the hemiketal) which then can be alkylated at C(4) to generate **XXX**.[26] For the case of the 4-methoxyphenol species **XXVI**, 1 equiv of MVK may be added to C(6) to generate the 2,4-dienone species **XXVII**. Treatment of this species with 1 equiv of MVK and base leads to the double alkylation product **XXIX**, shown in Figure 4.

Formation of *o*-Quinone Methides. The 2,3-η^2-*o*-cresol complex **III** in the presence of an excess of crotonaldehyde (~2 equiv) reacts cleanly to form two diastereomers of a C(4) conjugate addition product at room temperature.[27] However, when the reaction is attempted with the phenol complex **I** at this temperature, a mixture of three products results (Figure 3). Although two diastereomers of a C(4) Michael adduct (**VII**) can be identified, a third component of the reaction mixture, **XXIV**, results from an aldol condensation at C(6). Repeating the experiment with the addition of 1 equiv of DIEA accelerates the Michael addition to the point that the aldol product is not observed and the 2,5-cyclohexadienone complex **VII** is isolated as an equimolar mixture of C(3′) epimers. Likewise, the addition of BF_3·OEt_2 to the reaction mixture at 20 °C eliminates contamination from the aldol side reaction and two diastereomers of **VII** are obtained in approximately the same ratio as seen with base.[28] When excess crotonaldehyde is used in the absence of either base or Lewis acid, the *o*-quinone methide complex **XXIV** is generated as the dominant product (Figure 3).[29]

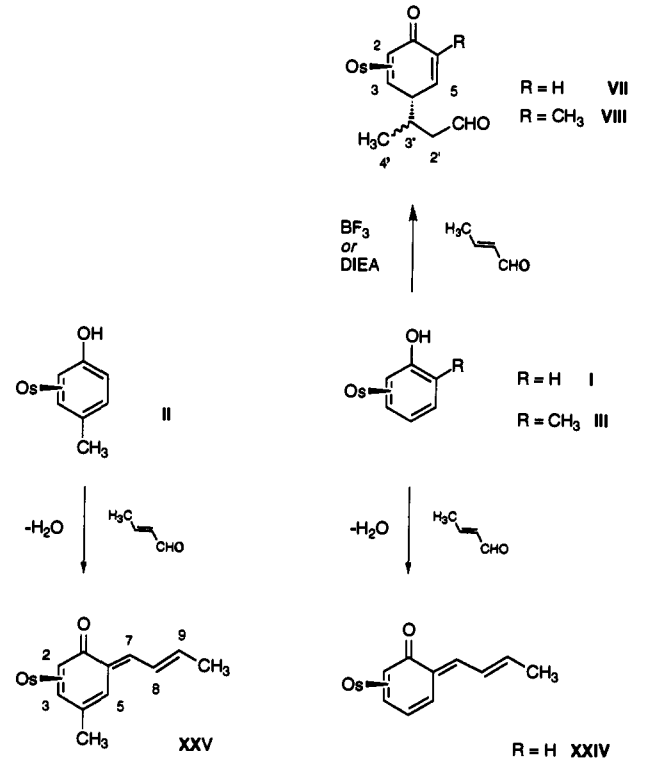


Figure 3. Formation of *o*-quinone methide complexes from η^2-phenols and crotonaldehyde and the competing Michael reaction at C(4).

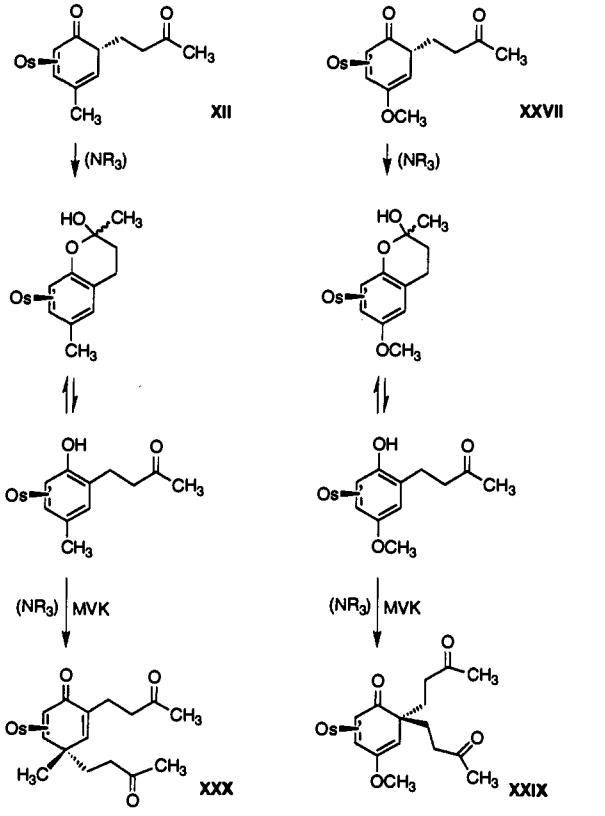


Figure 4. Double-alkylation products from the reaction of an η^2-phenol complex and an excess of methyl vinyl ketone (MVK).

(24) ^1H and ^{13}C NMR data for **XXIII**. ^1H NMR (CD_3CN): δ 6.18 (d, 1H, J = 12.0 Hz), 5.99 (d, 1H, J = 12.0 Hz), 5.57 (s, 1H), 4.77 (d, 1H, J = 7.8 Hz), 4.59 (br s, 3H, *trans*-NH_3), 4.38 (d, 1H, J = 7.8 Hz), 3.39 (br s, 12 H, *cis*-NH_3), 2.19 (s, 3H), 1.0–3.6 (m, 16H), 0.78 (s, 3H). ^{13}C NMR (CD_3CN): δ 205.3 (CO), 197.9 (CO), 166.8 (C), 134.9 (CH), 131.9 (CH), 126.3 (CH), 80.7 (CH), 55.5 (CH), 52.5 (CH), 51.6 (CH), 49.6 (CH), 46.7 (C), 43.6 (C), 37.4 (CH), 37.1 (CH_2), 35.4 (CH_2), 33.3 (CH_2), 30.8 (CH_2), 24.5 (CH_2), 23.3 (CH_2), 30.3 (CH_3), 11.5 (CH_3).

(25) Gingrich, D. E.; Kopach, M. E.; Harman, W. D.; Shen, T. Y. Unpublished results. ^1H and ^{13}C NMR data for **XXXII**. ^1H NMR (CD_3CN): δ 5.05 (s, 1H), 4.43 (br, 3H), 4.39 (d, 1H, J = 7.8 Hz), 3.64 (s, 3H, OCH_3), 3.55 (s, 3H, OCH_3), 3.25 (br, 12H), 2.70 (m, 2H), 2.54 (m, 2H), 2.10 (s, 3H). ^{13}C NMR (CD_3CN): δ 207.8 (C), 199.5 (C), 175.5 (C), 101.8 (CH), 82.4 (C), 60.9 (OCH_3), 56.4 (OCH_3), 51.6 (CH), 51.3 (CH), 38.4 (CH_2), 31.1 (CH_2), 29.4 (CH_3).

(26) In addition, when the η^2-*p*-cresol complex is treated with 1 equiv of triflic acid in the presence of MVK, significant amounts of **XXX** are formed.

(27) As an example, when **III** is treated with 1 equiv of crotonaldehyde in the presence of DIEA, a mixture (de = 60%) of 2,5-dienone complexes (**VIII**) results as shown in Figure 3. Judging from the absence of coupling interactions between H(3) and H(4) for either compound, the addition occurs anti to the site of metal coordination. Thus as with the phenol analog, the product **VIII** is a mixture of C(3′) epimers. Possible contamination by 2,4-dienone or aldol condensation products is estimated to be less than 3% judging from ^1H NMR data.

(28) Dropping the temperature to –40 °C with BF_3 increases the de to 60%, however, the *o*-quinone methide **XXIV** is again generated as a side product (30%).

In order to generate a sample of an *o*-quinone methide complex derived from crotonaldehyde and a phenol completely free from contamination by conjugate addition products, the *p*-cresol complex **II** was treated with an excess of crotonaldehyde in the absence of base catalyst. The resulting complex **XXV** shows widely separated cis and trans ammine resonances characteristic of a pentaammineosmium(II) complex with a side-bound ligand (i.e. η^2) and six olefinic proton resonances ranging from 4.7 to 7.0 ppm. On the basis of COSY, DEPT, and NOE data, the product is assigned as the C(2) aldol condensation product shown in Figure 3. NOE data further indicate that H(5) and H(8) are in close proximity, and a coupling constant of 14.7 Hz between H(8) and H(9) indicates the trans stereochemistry shown in Figure 3. In addition, a weak NOE between H5 and the C(10) methyl protons and the absence of any interaction between H(5) and H(9) support this structural and conformational assignment.[30]

Ligand Decomplexation. Both the 2,4- and 2,5-cyclohexadienone ligands are readily decomplexed by the one-electron oxidation of the osmium or by direct substitution. For the cases where the sp^3 carbon contains a proton, these dienone ligands are converted into the corresponding arene complexes by moderate heating (70–80 °C) or by catalytic base. Once formed, the arene ligand dissociates from the metal at the elevated temperature. For example, when the phenol/MVK adduct **IV** is heated in CD_3CN at 70 °C for 12 h, a ^1H NMR spectrum indicates virtually quantitative formation of 4-(4-hydroxyphenyl)-2-butanone (raspberry ketone) as verified by comparison of ^1H NMR data with those of the authentic material. Alternatively, oxidation of **IV** by oxygen or AgOTf also generates this ketone. In a similar fashion, the ortho addition product of MVK and the 5,6,7,8-tetrahydronapthol complex **XVII** can be readily demetalated with AgOTf or prolonged exposure to air to yield 1-(3-oxobutyl)-5,6,7,8-tetrahydro-2-naphthol (Table 3).

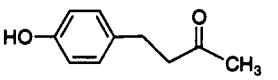
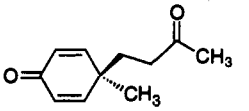
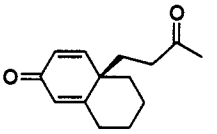
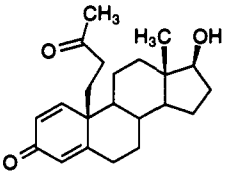
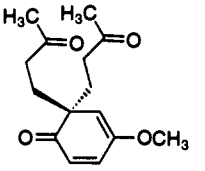
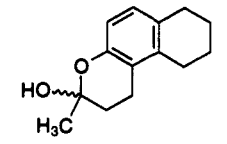
In contrast to the examples above, cyclohexadienone complexes which contain a quaternary sp^3 carbon resist tautomerization to an η^2-arene complex. As a consequence the oxidation of osmium requires a more powerful oxidant such as Ce(IV) or DDQ.[31] Thus, 4-(3-oxobutyl)-4-methyl-2,5-cyclohexadien-1-one is generated from the corresponding complex **XI** by treatment of the latter with 1.0 equiv of DDQ in CH_3CN (68%). In an analogous fashion, 2,5-dienone products were derived from osmium(II) complexes for several other cases, including the steroid 19-(2′-oxopropyl)-Δ^1-testosterone. Yield data for these organic products are summarized in Table 3.

The majority of the reactions described in this work were conducted under a rigorously controlled inert atmosphere on a small reaction scale. However, in order to better illustrate the potential utility of such a reaction sequence in the context of organic synthesis, the conjugate addition of MVK and *p*-cresol, a reaction considered to be typical of those reported herein, was scaled-up (1 g of $Os(NH_3)_5(OTf)_3$) and conducted on a lab bench using solvents directly as received from commercial sources. The overall isolated yield of the crude dienone product was 81% based on osmium. After purification by column chromatography, the isolated yield of 4-methyl-4-(3-oxobutyl)-2,5-cyclohexadien-1-one was 65% (150 mg).

Discussion

The electron-rich pentaammineosmium(II) core affects the conjugate addition of electrophiles to phenol in several ways.

Table 3. Final Yields of Various Organic Products Derived from Phenols using the Osmium(II) Dearomatization Methodology

	Overall Yield
	83%
	65%
	85%
	69%
	72%
	54%

Both crystallographic[5] and spectroscopic[32] evidence indicate that dihapto-complexation of an arene by an electron-rich transition metal partially localizes the π-electron density. Correspondingly, 2,3-η^2-phenols are expected to have increased reactivity with electrophiles at the C(6) and C(4) positions, relative to the free ligand. More significantly, the 2,4- or 2,5-cyclohexadienone ligands are considerably stronger π-acids than their arene precursors and, as such, greatly stabilize the electron-rich osmium(II).[7] As a consequence, electrophilic addition to the ring occurs with much greater facility for η^2-phenol complexes than for the analogous organic substrate where conjugate addition typically is observed at oxygen.[33]

This osmium(II)–η^2-arene methodology described herein is complementary to the more-established η^6-arene chemistry (e.g., ML_3 = $Cr(CO)_3$, $Mn(CO)_3^+$, or RuCp*) that has been successfully adapted to organic synthesis.[2,34] (Figure 5) In contrast to the η^2-arene complexes described herein, the electronegative metal in the η^6-arene systems activates the arene toward nucleophilic addition meta to the donor group. Subsequent oxidation of the cyclohexadienyl species leads to a meta-substituted arene. Alternatively, deprotonation of the arene ring followed by addition of an electrophile generates ortho-disubstituted products.

(29) Repeating this set of experiments with acrolein produces only Michael addition at C(4) even in absence of catalyst.

(30) A similar *o*-quinone methide has recently been obtained by replacing crotonaldehyde with either acetaldehyde or benzaldehyde, and the chemistry of these compounds is currently under investigation.

(31) 2,3-Dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) was found to be the most efficient oxidant. When **XIX** was treated with 1 equiv of DDQ, 5,6,7,8-tetrahydro-4a*H*-(3-oxobutyl)-naphthalen-2-one was liberated in 85% yield. In general, yields of 2,5- and 2,4-dienone products were found to be 10–40% better when DDQ was used as an oxidant rather than Ce(IV).

(32) Harman, W. D. Ph.D. Dissertation, Stanford University, 1987.

(33) Conjugate addition reactions with phenols (including those without para substitution) typically occur at oxygen under basic conditions; under acidic conditions, electrophilic substitution has been observed at C(4) (e.g., phenol/MVK), but there are no reports of C(4) conjugate addition with para-alkylated phenols.

(34) (a) Semmelhack, M. F. *Pure Appl. Chem.* **1981**, 53, 2379. (b) Semmelhack, M. F. *J. Organomet. Chem. Libr.* **1976**, *1*, 361.

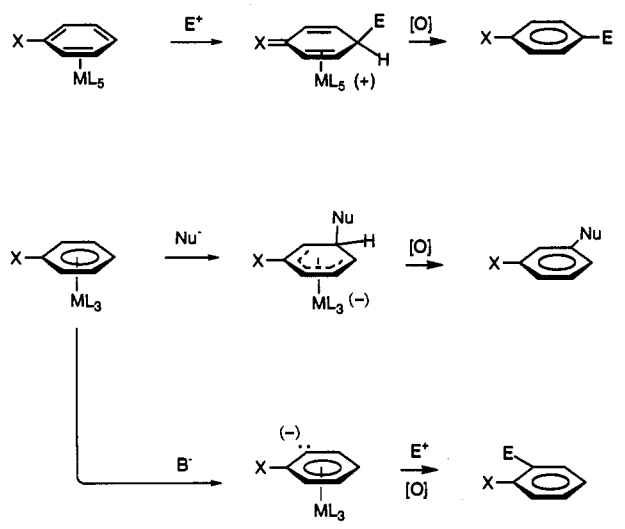


Figure 5. Schematic comparison of methods for the activation of arenes by transition metals: X = electron-donating group, B = base, Nu = nucleophile, E = electrophile.

The regioselectivity of the conjugate addition reaction varies according to the phenol substitution pattern, type of Michael acceptor, and reaction conditions, especially in cases where C(4) is alkylated (Table 2). Although the experimental observations made in this study do not support a full mechanistic analysis, some interpretation as to the origins of this regioselectivity may prove useful. For the phenol complex I, in every case examined, conjugate addition occurs exclusively at C(4). This feature appears to be general for η^2-arene complexes of pentaammineosmium(II) containing an electron-donating group; conjugate addition at C(4) has also been observed with the corresponding η^2-aniline and η^2-anisole complexes of pentaammineosmium(II).[35] In contrast, 4-alkylated phenols such as the *p*-cresol complex **II** show a tendency toward C(6) addition. *For a given η^2-phenol complex, there is a significnat correlation between the relative thermodynamic stability of the two dienone isomers of this complex*[7] *and the regiochemistry observed when this complex undergoes a Michael reaction.* This correlation is especially true when the reaction is carried out in the presence of base and a Zn^{2+} cocatalyst. When the phenol complex I is equilibrated with its dienone tautomers in acidic or basic methanol, the 2,5-dienone species is the only detectable tautomer aside from I.[7] A similar result is obtained for the *o*-cresol and *m*-cresol analogs. In contrast, for the η^2-*p*-cresol II and 3,4-dimethylphenol systems, the 2,4-cyclohexadienone complex is thermodynamically favored over its 2,5-dienone isomer.[7,36] This difference may be ascribed to either the increased stabilization for the 2,4-cyclohexadienone species as a result of substitution on the C(4)–C(5) double bond or to a decrease in stability of the 2,5-cyclohexadienone species as a result of a steric repulsion between the ammine ligands and the tetrahedral C(4) substituent.

A plausible mechanistic scheme for a base-catalyzed Michael addition is shown for the example of the *p*-cresol complex **II** reacting with *N*-methylmaleimide in Figure 6. Under conditions where protonation of the enolates is rate-limiting, the two possible intermediates, **XIV-En** and **XV-En**, will reach a state of pre-equilibrium. Given that the activation energies for protonation of these enolates will not be affected by any differences in their dienone components,[37] the ratio of products (**XIV** and **XV**) should directly correlate with the thermodynamic stability of the enolate intermediates. Furthermore, the relative stabilities of the ortho and para enolates should be similar to those of the corresponding dienone isomers for the phenol precursor. Thus, for moderate reaction temperatures (e.g. 20 °C) or in the presence of the Zn^{2+} cocatalyst, the observed product of conjugate addition is typically the dienone analogous to the thermodynamically preferred isomer of the corresponding phenol complex, *even though the overall reaction is under kinetic control.*[38]

At reduced temperatures or in the presence of a protic solvent, many of the base-catalyzed reactions show a dramatic enhancement in their para/ortho product ratio, provided that Lewis acid cocatalysts are excluded. Consider, for example, the reaction of MVK with the β-estradiol complex **XX** in CH_3CN. At 20 °C, addition at C(4) ortho to the hydroxy group is the dominant reaction (**XXII**), but when the reaction is repeated at −35 °C, the regiochemistry is reversed and a para addition product (**XXI**) is formed exclusively (i.e., alkylation at C(10)).[39] A similar observation is made for the addition of *N*-methylmaleimide or MVK to the *p*-cresol complex (Table 2). Apparently, the para addition pathway in these cases (e.g., formation of enolate **XIV-En** in Figure 6) is kinetically favored. Thus, under conditions where protonation is not rate-limiting, a para addition may be achieved in some cases even if the ortho enolate (e.g., **XV-En**) and ortho addition product (e.g., **XV**) are thermodynamically more stable.[40]

Why, then, is para addition kinetically favored for many of the reactions involving 4-alkylated η^2-phenols? Extended Hückel calculations suggest that the HOMO of these phenol complexes has the largest coefficient on the para carbon. Since the HOMO electrons are expected to be most polarizable, a para addition should be kinetically favored, assuming that the conjugate addition of the phenolate complex and the Michael acceptor has a late transition state. Another intriguing possibility, however, is that, under certain conditions, a Diels–Alder reaction occurs between the dienolate fragment of the arene complex and the Michael acceptor. If the hypothesized bicyclo[2.2.2]octadiene ligand were unstable with respect to a retro-aldol reaction (Figure 6), the resulting product would be indistinguishable from one derived from a direct conjugate addition. This reaction sequence not only would explain the unusually large preference for the para position at low temperatures but also lends interpretation to the high stereoselectivity observed at the β-carbon of the Michael acceptor (*vide supra*). Compounds **V**, **VI**, **VIII**, and **XIV** and the Michael product from cyclopentenone and *p*-cresol (Table 2, run 11) all are formed as one dominant diastereomer despite having three independent asymmetric groups. Here, the ratio of exo/endo cycloaddition products would directly determine this stereochemistry (Figure 6). Indirect evidence for such a mechanism comes from the comparison of the reactions of the *p*-cresol complex **II** with MVK and its α-methylated analog. Whereas MVK adds para to the hydroxy group of the cresol ligand of **II** in the presence of BF_3 or DIEA, the same reaction with 3-methyl-3-buten-2-one delivers only the ortho adduct with the Lewis acid and fails completely with the base (Table 2, runs 9 and 10). Here, the hypothesized cycloadduct intermediate, which would lead to a C(4) addition product, is sterically encumbered by the α-methyl group of the Michael acceptor (i.e., dienophile), and as a consequence, this pathway appears to be preempted by conjugate addition to C(6).

Despite our efforts, a stable bicyclo[2.2.2]octadiene species has not been isolated from any reaction with an η^2-phenol species

(35) Gonzalez, J.; Sabat, M.; Harman, W. D. *J. Am. Chem. Soc.* **1993**, *115*, 8857. Kopach, M. E.; Gonzalez, J.; Harman, W. D. *J. Am. Chem. Soc.* **1991**, *113*, 8972. Harman, W. D.; Kopach, M. E. Unpublished results.

(36) For the η^2-*p*-cresol system, the phenolic form is the dominant tautomer; however, the 2,4-dienone is observable by ^1H NMR after equilibration in acidic methanol. The 2,5-dienone tautomer is not observed.

(37) The enolate groups in **XIV-En** and **XV-En** are not conjugated to the dienone system.

(38) The dienone complexes **XV** and **XIV** fail to interconvert when subjected to DIEA and/or Zn^{2+}; thus, protonation of the enolate is considered to be irreversible.

(39) If Zn^{2+} is added to the reaction mixture, the ortho product **XXII** is formed even at the reduced temperature. See ref 9.

(40) Presumably, when Zn^{2+} is added to the reaction mixture, the thermodynamic enolate becomes accessible even at lower temperatures.

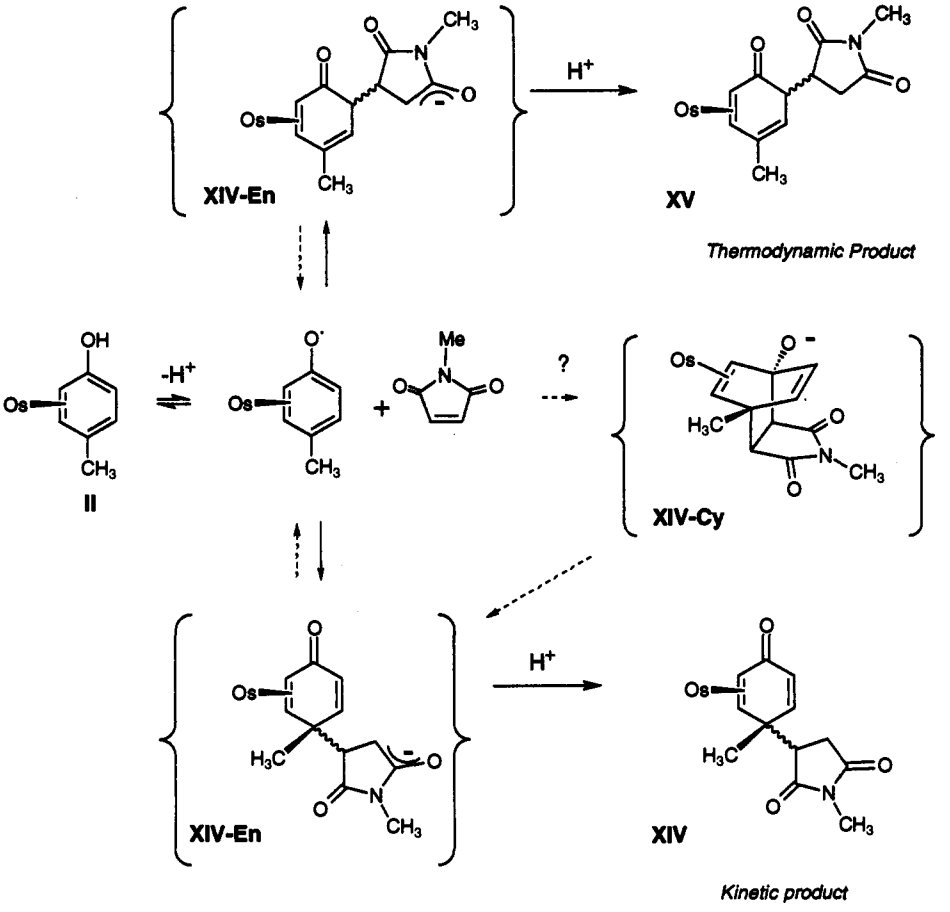


Figure 6. Possible mechanistic scheme for the net conjugate addition of *N*-methylmaleimide to the η^2-*p*-cresol complex **II** in the presence of base catalyst.

under either basic or acidic conditions.[41] However, we have recently found that the η^2-anisole derivative of I reacts with *N*-methylmaleimide (CH_3CN) in the presence of $BF_3 \cdot Et_2O$ at −50 °C to yield a stable, isolable cycloaddition product similar to the intermediate **XIV-Cy** shown in Figure 6. Repeating this reaction for longer reaction times delivers only a C(4) Michael substitution product, but we have shown that the cycloadduct is not an intermediate in this process.[42] Yet the observation of a stable cycloadduct intermediate for anisole suggests that a [4 + 2] cycloaddition for η^2-phenols should also be kinetically accessible and that this mechanism may play a role in the base-catalyzed process.

In an earlier study, the conversion of η^2-cyclohexadienones to η^2-arenes was shown to be rapid on pentaammineosmium(II) under moderately acidic conditions (~0.1 M HOTf/MeOH).[7] In these examples, however, the cyclohexadienone complexes were formed from their η^2-arene isomers. As such, these complexes have anti-oriented sp^3-methine hydrogens (pointing away from the metal) and are readily accessible by a potential base (i.e., the solvent). In contrast, the 2,5- or 2,4-cyclohexadienone conjugate addition products reported herein have a syn sp^3-methine hydrogen; owing to the size of the pentaammine moiety, the coordinated face of the arene is screened from approach of the Michael acceptor and addition occurs to the exo ring face (opposite that of coordination). As a consequence, the sp^3-methine proton is forced into a pocket (endo stereochemistry) which hinders its removal (e.g., solvent). Thus, in addition to the pronounced effect that coordination has upon the arene–dienone equilibrium,[7] the pentaammineosmium(II) moiety stabilizes these dienone complexes from rearomatization by blocking the acidic sp^3-methine proton at either C(4) or C(6). As an example, consider the 2,5-dienone addition product of MVK and phenol, **IV**, which is stable

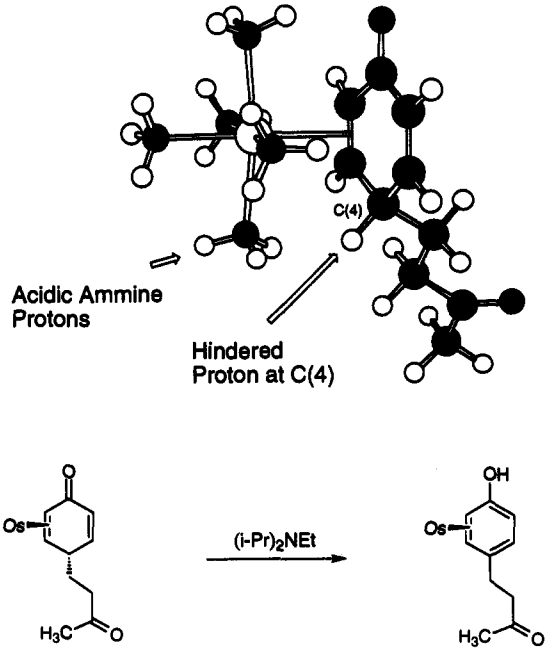


Figure 7. Model of the kinetically stable 2,5-cyclohexadienone complex **XI**, the product of conjugate addition of the η^2-*p*-cresol complex **II** and MVK.

in moderately acidic (~0.1 M HOTf) or basic (0.1 M pyridine) methanol for 24 h. Even though this product is known to be unstable with respect to its phenolic tautomer, inspection of an optimized (MM2) molecular model (Figure 7) of the dienone illustrates the extent to which the C(4) proton is blocked. Only upon extended exposure to more basic catalysts (e.g. DIEA) does **IV** convert to the phenolic form. In view of these steric restraints,

(41) Even at −80 °C, cycloaddition for η^2-phenols is not observed.
(42) Kopach, M. E.; Harman, W. D. Submitted for publication.

rearomatization most likely occurs by initial deprotonation of one of the *cis*-ammine ligands.[43] Subsequent intramolecular deprotonation of the sp^3-ring carbon would restore the phenolic form of the ligand. This high kinetic barrier to rearomatization provides the opportunity to introduce a nucleophile at C(3). An example of such a reaction has recently been demonstrated for an η^2-aniline complex in which 2 equiv of an activated olefin are combined with the arene in a Michael–Michael ring closure (MIMIRC) sequence to generate a highly substituted *cis*-decalin system,[44] and preliminary experiments with these η^2-2,5-cyclohexadienone complexes suggest that both intra- and intermolecular nucleophilic additions may be realized.

Cyclohexadienones have proven to be highly versatile synthons for functionalized alicyclic systems of which steroidal systems are prime examples.[45,46] Although modest yields of both 2,4- and 2,5-cyclohexadienones have been prepared by the alkylation of phenoxide salts,[35] the tendency of these salts to alkylate at oxygen has precluded the development of any general method. The formation of cyclohexadienones via the intermolecular conjugate addition of phenols or phenolates appears to be unprecedented. Through the η^2-coordination by osmium, the electronic properties of a phenol are modified to the point that Michael additions at C(4) and C(6) may be carried out under mild conditions to deliver 2,4- and 2,5-cyclohexadienones in good overall yield (65–85%) from a three-step process of complexation/addition/decomplexation. These findings illustrate the potential of transition-metal reagents which can bind aromatic molecules across a single π-bond.

Acknowledgment. We thank the donors of the Petroleum Research Fund, administered by the American Chemical Society (PRF No. 26027-AC), the Camille and Henry Dreyfus Foundation, the National Science Foundation (CHE-9212008 and the NYI program), and Colonial Metals Inc. (Elkton, MD; OsO_4) for their generous support of this work.

(43) The ammine protons of the pentaammineosmium(II) complexes reported in this work are readily exchanged with deuterium in D_2O solution in the presence of DIEA.

(44) Gonzalez, J.; Sabat, M.; Harman, W. D. *J. Am. Chem. Soc.* **1993**, *115*, 8857.

(45) Waring, A. J. *Adv. Alicyclic Chem.* **1966**, *1*, 129.

(46) For recent examples, see: (a) Takano, S.; Higashi, Y.; Kamikubo, T.; Moriya, M.; Ogasawara, K. *Synthesis* **1993**, 948. (b) Gates, B. D.; Dalidowicz, P.; Tebben, A.; Wang, S.; Swenton, J. S. *J. Org. Chem.* **1992**, *57*, 2143. (c) Carpenter, K.; Chen, Y.; Kerns, M. L.; Morrow, G. W. *J. Org. Chem.* **1993**, *58*, 3308.