

Stereoselective Tandem 1,4-Addition Reactions for Benzenes: A Comparison of Os(II), Re(I), and W(0) Systems

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Abstract: The arene ligand in the complex $\text{TpRe}(\text{CO})(\text{Melm})(\eta^2\text{-benzene})$ (Tp = hydridotris(pyrazolyl)-borate; Melm = *N*-methylimidazole) undergoes tandem electrophile/nucleophile 1,4-addition reactions. Subsequent oxidative demetalation affords *cis*-3,6-disubstituted 1,4-cyclohexadienes (46–84%). Common organic electrophiles such as acetals and Michael acceptors were successfully added to the bound benzene to generate η^3 -benzenium complexes, which then were treated with a silyl ketene acetal, silyl vinyl ether, phenyllithium, or malonate ester to afford 1,4-dialkylated dihydrobenzene complexes. The d^6 transition metal analogues $\text{TpW}(\text{NO})(\text{PMe}_3)(\eta^2\text{-benzene})$ and $[\text{Os}(\text{NH}_3)_5(\eta^2\text{-benzene})]^{2+}$ also undergo 1,4-dialkylation reactions, and the relative ability of all three metals to activate arenes is compared.

Introduction

Transition metals have been used widely to promote the dearomatization of benzenes.¹ Electron-deficient metal fragments such as $\{\text{Cr}(\text{CO})_3\}$, $\{\text{Mn}(\text{CO})_3\}^+$,^{1,2} and more recently $\{\text{Mo}(\text{CO})_3\}$ ³ activate η^6 -coordinated arenes toward a nucleophilic addition. In some cases, this action can be followed by an electrophilic addition to the cyclohexadienyl ligand, sometimes concomitant with CO insertion, giving rise to *trans*-5,6-disubstituted 1,3-cyclohexadienes. As a complementary methodology, we have explored the chemistry of the pentaammine-osmium(II) fragment, which, through back-bonding, functions as an electron donor when dihapto-coordinated to an arene. These complexes readily undergo reactions with electrophilic reagents.⁴ The resultant η^3 -arenium complexes can react with various nucleophiles to provide *cis*-3,6-disubstituted 1,4-cyclohexadienes, which in turn can be liberated from the metal by oxidation (Figure 1).⁵ Due to the high Brønsted acidity of osmium(II)-arenium complexes ($\text{p}K_a$ ranges from -8 to -10),⁶ the yield of this tandem addition sequence is generally low, especially for more basic nucleophiles,⁵ where deprotonation often preempts the intended nucleophilic addition reaction (Figure 1).

Recently, we have developed a series of second generation π -bases using rhenium,⁷ molybdenum,⁸ and tungsten.⁹ In

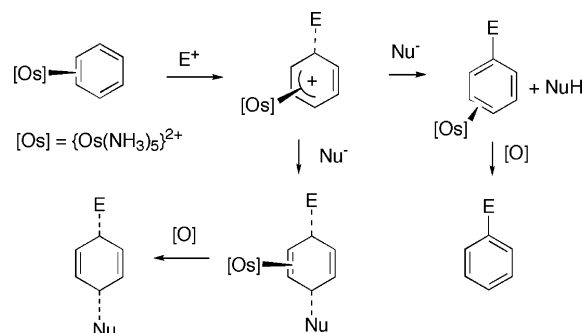


Figure 1. Tandem addition sequence for an osmium(II)- η^2 -benzene complex.

particular, the $\{\text{TpRe}(\text{CO})(\text{MeIm})\}$ and $\{\text{TpW}(\text{NO})(\text{PMe}_3)\}$ fragments are capable of forming complexes with benzene that rival the thermal stability of $[\text{Os}(\text{NH}_3)_5(\eta^2\text{-benzene})]^{2+}$.¹⁰ We anticipated that the rhenium and tungsten benzene complexes would be more reactive toward electrophiles than their osmium counterpart due to their greater ability to back-bond.⁹ In addition, the resulting arenium complex would be less susceptible to deprotonation by an intended nucleophile.^{11–13} We herein report that tandem 1,4-additions to benzene can be realized with these new Re(I) and W(0) reagents, with improved yields and a wider scope of nucleophile than is possible with the analogous osmium(II)-mediated reactions.

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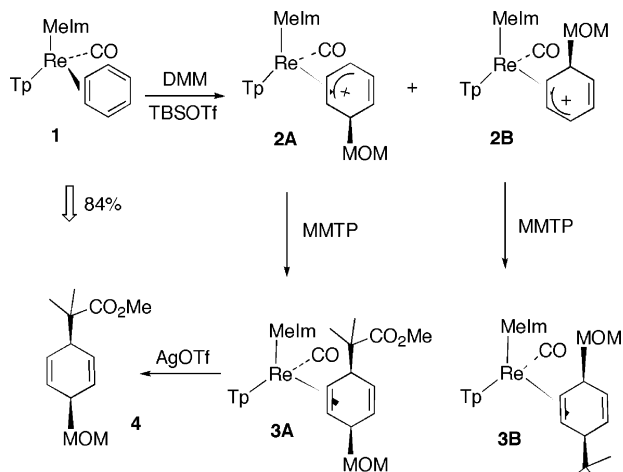


Figure 2. Tandem addition reaction sequence for the rhenium(I)-benzene complex **1**.

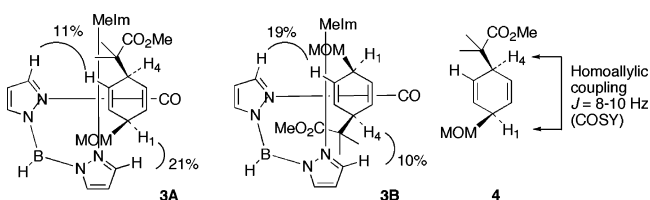


Figure 3. NOE interactions confirming the stereochemical assignment of diastereomers **3A** and **3B**.

Results and Discussion

When $\text{TpRe}(\text{CO})(\text{MeIm})(\eta^2\text{-benzene})$ (**1**) was treated with dimethoxymethane (DMM) in the presence of triflic acid (HOTf), under optimal reaction conditions found for the $[\text{Os}(\text{NH}_3)_5(\eta^2\text{-benzene})]^{2+}$, decomposition of the complex was accompanied by the appearance of benzene. The use of other reaction promoters such as trifluoroacetic acid or lithium triflate along with DMM resulted in either recovery or decomposition of the starting complex, depending on the reaction temperature. However, when a mixture of **1** and DMM in acetonitrile was treated with TBSOTf at -20°C , a benzenium species **2** was observed by ^1H NMR with a 1:1 diastereomeric ratio (**2A**:**2B**; Figure 2). A COSY spectrum of this mixture reveals two isolated spin systems for the allyl protons at 5.04, 4.72, 4.55 ppm and 5.09, 4.80, 4.49 ppm. Due to extensive overlap of signals, the Tp region (6–8 ppm) of the spectrum could not be assigned, and NOE data failed to reveal the orientation of the arenium ligands. However, when a solution of the benzenium complex **2** was treated with 1-methoxy-2-methyl-1-(trimethylsilyloxy)propene (MMTP) at -20°C , complex **3** was isolated as a mixture of two coordination diastereomers (Figure 2), which were separated through preparatory TLC on silica. 1D NOE experiments allowed the assignment of **3A** and **3B**, as shown in Figure 3.

Apparently, the regio- and diastereoselectivity of the tandem addition reaction follows the same pattern as observed for the pentaammineosmium(II) benzene complex, where a *cis*-3,6-dialkylated-1,4-cyclohexadiene complex is formed. IR spectra of complexes **3A** and **3B** show $\text{C}=\text{O}$ stretching frequencies at 1788 and 1786 cm^{-1} , respectively, consistent with a $\text{TpRe}(\text{CO})$ -

Table 1. Products and Yields of Tandem Addition Reactions to Benzene^a

Electrophile	Nucleophile	product	overall yield [Re] [Os]
			4 84% 82%
			5 76% 0%
	PhLi/CuCN		6 71% 16%
			7 46% 23%
			8 56% 0%

^a [Re] = $\text{TpRe}(\text{CO})(\text{MeIm})$; [Os] = $[\text{Os}(\text{NH}_3)_5]^{2+}$.

(MeIm)(olefin) complex.¹⁴ Unlike $\text{TpRe}(\text{CO})(\text{MeIm})(\eta^2\text{-ethylene})$, which has a reversible redox couple at -0.03 V ,¹⁴ complexes **3A** and **3B** exhibit chemically irreversible anodic peaks (each at 0.21 V). This difference is likely to be due to the presence of bulky substituents on the ligand, which facilitate the ligand substitution process. Upon oxidative demetallation with silver triflate (AgOTf) at 75°C , cyclohexadiene **4** was isolated in 84% overall yield from the benzene complex **1** (see Figure 2).

Methyl vinyl ketone (MVK) failed to add to the pentaammineosmium(II)-benzene complex,⁵ most likely because this reaction was preempted by polymerization of MVK under the acidic conditions required. However, when complex **1** was treated with MVK in the presence of TBSOTf followed by MMTP, **5** was isolated in 76% yield upon its decomplexation (Table 1). Similar to other *cis*-3,6-disubstituted 1,4-cyclohexadienes, ^1H NMR data for **5** reveals symmetric splitting of olefinic protons around 5.63 ppm and strong homoallylic coupling between the H1 and H4 protons (3.13 and 2.77 ppm). Alternatively, phenyllithium (in the presence of copper cyanide) was found to react with the benzenium intermediate **2**, giving the 1-aryl-4-alkyl addition product **6** in 71% yield.

Compared with the pentaammineosmium(II), the strongly electron-donating fragment $\text{TpRe}(\text{CO})(\text{MeIm})$, stabilizes the benzenium complexes that result from electrophilic addition. In addition, the bulky ligand set of this fragment hinders the nucleophile from deprotonating the sp^3 carbon (C1). This notion is clearly demonstrated in the nucleophilic addition of trimethylsilyloxypropene or dimethyl malonate to the benzenium ligand of $\{\text{TpRe}(\text{CO})(\text{MeIm})\}$ compared to $\{\text{Os}(\text{NH}_3)_5\}^{2+}$. The vinyl ether 2-trimethylsilyloxypropene readily adds as a nucleophile to the osmium(II)-benzenium complex at -40°C ,⁵ but it showed no reaction with the rhenium analogue (**2**). However, in the presence of sodium iodide, the desired reaction between **2** and this vinyl ether proceeded to form **7** in 46% yield. When the pentaammineosmium(II) complex was treated with DMM followed by dimethyl malonate and DBU, benzyl methyl ether was observed with no detectable amount of the tandem addition product. In contrast, in the presence of

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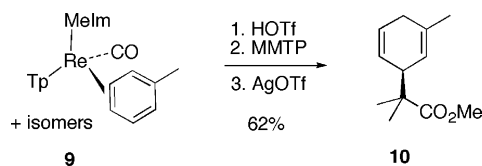


Figure 4. Tandem addition reaction sequence with an η^2 -toluene complex.

DBU, dimethyl malonate reacted smoothly with the benzenium complex **2** (prepared in situ), affording **8** in an overall 56% yield. As seen in Table 1, the yields for the rhenium(I)-promoted reactions are generally superior to those realized with osmium, largely due to the increased stability of the arenium intermediates for the group VII metal. When the benzene complex **1** was treated with the weaker electrophiles acrylonitrile or methyl acrylate and TBSOTf followed by MMTP, an intractable mixture resulted. For the latter case, proton data for the complex mixture suggested that 2 equiv of methyl acrylate added in a Michael–Michael ring closure sequence, similar to that observed earlier in our laboratories for an osmium(II)- η^2 -aniline complex,¹⁵ but the mixture of purported isomers could not be separated.

The coordination of the {TpRe(CO)(MeIm)} fragment to toluene results in multiple new species (four major) in equilibrium, as both regio- and stereoisomers are now possible. Whereas the benzene complex **1** decomposed in the presence of HOTf, when the toluene complex (**9**) was treated with HOTf followed by MMTP, the 1,4-cyclohexadiene **10** was formed in 62% yield, after its oxidative decomplexation with AgOTf (Figure 4). Despite a mixture of both linkage and stereoisomers for **9**, a single organic product was isolated (Figure 4). As was observed for the osmium analogue, protonation occurs at the ortho carbon and addition to the 1*H*-arenium intermediate occurs at C4. Unfortunately, we have not been successful in adding acetals or Michael acceptors to the toluene or xylene complexes, most likely as a result of the very short substitution half-life for these more sterically hindered arene complexes. Anisole, on the other hand, forms a complex with TpRe(CO)(MeIm) that is *more* substitution inert than **1**, and the π -donating methoxy group greatly facilitates the addition of carbon electrophiles at C4. A full investigation into rhenium and tungsten anisole and 4*H*-anisole chemistry is forthcoming.¹⁶

Previously, we have reported that η^2 -naphthalene complexes of rhenium¹⁷ and molybdenum⁸ undergo 1,2- or 1,4-tandem addition reactions similar to those reported herein. The more delocalized nature of the C–C bonds in benzene, relative to PAHs, make dearomatization of the former a particularly difficult challenge. However, the complex TpW(NO)(PMe₃)-(η^2 -benzene) (**11**) was recently reported as being synthesized from W(CO)₆.⁹ The fragment {TpW(NO)(PMe₃)} is thought to be an even stronger π -base than its rhenium analogue. Consistent with this notion, complex **11** readily decomposes, even at -40 °C, in the presence of various acids including HOTf, BF₃·Et₂O, TBSOTf, MSA, and TFA. Nevertheless, the mild Brønsted acid Ph₂NH₂OTf can be used at -40 °C (or TBSOTf at -78 °C) as a promoter for electrophilic addition.

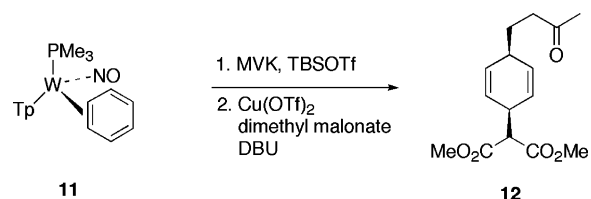


Figure 5. 1,4-Dialkylation addition with a tungsten(0)- η^2 -benzene complex.

When complex **11** was combined with MVK under these conditions, the subsequent treatment of this reaction mixture with pyridine followed by AgOTf afforded 4-phenylbutan-2-one¹⁸ in 90% yield. Following the addition of MVK, a variety of nucleophiles were tested, including those reported in Table 1 and vinylmagnesium bromide. Subsequent demetalation with AgOTf at room temperature followed by heating yielded only the monosubstituted benzene. Apparently, the benzenium resulting from Michael addition was stabilized by the tungsten fragment to a greater extent relative to the osmium and rhenium analogues, resulting in a diminished electrophilicity of the benzenium complex. We reasoned that the reactivity of the benzenium ligand for this tungsten system could be increased by the one-electron oxidation of the metal. Indeed, when a cold solution of the purported benzenium intermediate prepared from **11** and MVK was treated with the oxidant Cu(OTf)₂ at -78 °C *immediately* after the addition of dimethyl malonate and DBU, cyclohexadiene **12** was isolated in 25% yield (Figure 5). Interestingly, even slightly milder oxidants such as AgOTf did not promote the nucleophilic addition of malonate. Finally, we note that while no η^2 -benzene complexes of a second-row transition metal have been shown to undergo tandem addition reactions, the complex TpMo(NO)(MeIm)(η^2 -naphthalene) undergoes protonation followed by MMTP addition to afford a 1,2-dihydronaphthalene in 80% yield.⁸

Experimental Section

General Procedure. All the reactions were performed under nitrogen in a Vacuum Atmospheres Co. glovebox. ¹H and ¹³C NMR spectra were collected on a 300 or 500 MHz Varian INOVA spectrometer. Chemical shifts are reported in parts per million relative to tetramethylsilane (TMS) using the deuterated solvents as the internal reference, and coupling constants are reported in Hertz. COSY and HETCOR experiments were carried out by using the standard parameters. The following abbreviations will be used to discriminate among the pyrazolyl rings: ^{co}Tp = pyrazolyl ring trans to CO, ^oTp = pyrazolyl ring trans to the olefin, ^{im}Tp = pyrazolyl ring trans to MeIm. Infrared spectra (IR) were recorded on a MIDAC Prospect Series (Model PRS) spectrometer as a glaze (evaporated diethyl ether) on a Horizontal Attenuated Total Reflectance (HATR) accessory (Pike Industries). Electrochemical experiments were performed under a dinitrogen atmosphere using a PAR Model 362 potentiostat driven by a PAR Model 175 universal programmer. Cyclic voltammograms (CV) were recorded (Kipp and Zonen BD90 XY recorder) at 100 mV/s (25 °C) in a standard three-electrode cell from +1.7 to -1.7 V with a glassy carbon working electrode, dimethylacetamide (DMA) solvent, and tetrabutylammonium hexafluorophosphate (TBAH) electrolyte. All potentials are reported versus NHE (normal hydrogen electrode) using cobaltocene ($E_{1/2} = -780$ mV) as an internal standard. HRMS determination was performed in the laboratory of mass spectrometry at the University of Illinois, Urbana-Champaign.

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Reagents. All the solvents and electrophiles were purified via distillation under nitrogen or passage through an activated alumina column under nitrogen. The syntheses of $\text{TpRe}(\text{CO})(\text{MeIm})(\eta^2\text{-benzene})$ and $\text{TpW}(\text{NO})(\text{PMe}_3)(\eta^2\text{-benzene})$ were previously reported,^{4,9} as were compounds **4**, **6**, **7**, and **10**.³

Compound 4 (Example of One-Pot Procedure). To the rhodium(I)–benzene complex (50 mg, 0.085 mmol), CH_3CN (10 mg, 0.128 mmol) and 0.5 g of DMM were added and the solution was cooled to -20°C before TBSOTf (34 mg, 0.13 mmol) was added and allowed to sit for 12 min. A chilled acetonitrile (0.3 g) solution (-20°C) of MMTP (84 mg, 0.48 mmol) was added and allowed to sit for 0.5 h and then 0.5 h at 25°C . AgOTf (22 mg, 0.086 mmol) was added and the reaction mixture was transferred to a 75°C oil bath for 1.0 h. After cooling to 25°C the solvents were evaporated, and 1 mL of water was added to dissolve the oil-like residue. Then 40 mL of ether was added. The ether layer was then evaporated, and the residue was dissolved in chloroform and subjected to chromatography. The elution of 10% ethyl acetate in hexanes on silica gel yielded the product (16 mg, 84%, $R_f = 0.30$) visualized by the stain of iodine. In the case of methyl vinyl ketone as the electrophile, tetrahydrofuran (THF) was used as the reaction solvent.

[TpRe(CO)(MeIm)(2,3,4- η^3 -(1-Methoxymethyl-1H-benzium)]-(OTf) (2). To the benzene complex **1** (50 mg, 0.085 mmol), 0.5 g of CD_3CN and DMM (7 mg, 0.09 mmol) were added and then cooled to -20°C before TBSOTf (22 mg, 0.083 mmol) was added. Two diastereomers were observed (^1H NMR) with a 1:1 ratio. Due to overlapping, resonances for the Tp ligand could not be assigned. ^1H NMR (500 MHz, -20°C): δ 6.43 (2 \times 1H, m, H3), 5.33 (2 \times 1H, m, H2), 5.09, 5.04 (each 1H, d, $J = 2.0$, H6), 4.80, 4.72 (each 1H, dd, $J = 2.0$, 2.0, H5), 4.55, 4.49 (each 1H, d, $J = 2.0$, H4), 3.83, 3.77 (each 1H, m, H1), 3.67, 3.63 (each 2 \times 1H, m, CH_2OCH_3), 3.32, 3.32 (each 3H, s, CH_2OCH_3). ^{13}C NMR (125 MHz, -20°C): δ 131.8, 130.4 (C3), 126.2, 125.8 (C2), 97.4, 92.9 (C6), 97.3 (2 \times C4), 78.6, 74.3 (C5), 74.2 (2 \times CH_2OCH_3), 54.7 (2 \times CH_2OCH_3).

TpRe(CO)(MeIm)(5,6- η^2 -(Methyl 2-[4-(methoxymethyl)cyclohexa-2,5-dien-1-yl]-2-methylpropanoate) (3). An acetonitrile solution (1.0 g) of $\text{TpRe}(\text{CO})(\text{MeIm})(\eta^2\text{-benzene})$ (100 mg, 0.170 mmol) and DMM (20 mg, 0.26 mmol) was cooled to -20°C and treated with a chilled (-20°C) acetonitrile solution (0.3 g) of TBSOTf (68 mg, 0.26 mmol). After 12 min the reaction was treated with a chilled (-20°C) acetonitrile solution (0.5 g) of MMTP (168 mg, 0.966 mmol). After an hour, 2,6-lutidine (30 mg, 0.28 mmol) was added and then the reaction mixture was added dropwise into 30 mL of stirring hexanes. The oily precipitate was loaded onto a 500 μm TLC silica plate and eluted with 1:1 hexanes:ethyl acetate. The desired bands were cut off and washed with acetonitrile (1.0 g). The solvents were removed under reduced pressure to yield the product as a yellow solid. Diastereomer **3A** ($R_f = 0.36$, 32 mg, 26%) CV $E_{p,a} = 214$ mV (NHE). IR (HATR, glaze): $\nu_{\text{BH}} = 2476$ cm^{-1} , $\nu_{\text{CO}} = 1788$, 1720 cm^{-1} . ^1H NMR (500 MHz) (acetonitrile- d_3): δ 7.91 (1H, d, $J = 1.9$, $^{\text{O}}\text{Tp-H5}$), 7.86 (1H, d, $J = 2.6$, $^{\text{CO}}\text{Tp-H5}$), 7.76 (1H, d, $J = 2.6$, $^{\text{CO}}\text{Tp-H3}$), 7.71 (1H, m, Im), 7.65 (1H, d, $J = 1.9$, $^{\text{O}}\text{Tp-H3}$), 7.59 (1H, d, $J = 1.9$, $^{\text{Im}}\text{Tp-H5}$), 7.32 (1H, d, $J = 1.9$, $^{\text{Im}}\text{Tp-H3}$), 6.84 (1H, dd, $J = 1.6$, 1.6, Im), 6.54 (1H, m, MeIm), 6.38 (1H, dd, $J = 2.6$, $^{\text{CO}}\text{Tp-H4}$), 6.19 (1H, dd, $J = 1.9$, 1.9, $^{\text{O}}\text{Tp-H4}$), 6.05 (1H, dd, $J = 1.9$, 1.9, $^{\text{Im}}\text{Tp-H4}$), 5.76 (1H, m, H3), 5.46 (1H, m, H2), 3.67 (3H, s, COOCH_3), 3.49 (3H, s, MeIm), 3.42 (1H, dd, $J = 6.1$, 2.6, CH_2OCH_3), 3.31 (1H, m, H4), 3.16 (1H, d, $J = 8.3$, CH_2OCH_3), 3.13 (3H, s, CH_2OCH_3), 3.07 (1H, m, H1), 2.28 (1H, dd, $J = 9.9$, 1.3, H5), 1.98 (1H, dd, $J = 9.9$, 1.3, H6), 1.09 (3H, s, gem Me), 0.89 (3H, s, gem Me). ^{13}C NMR (125 MHz): δ 199.0 (C=O), 179.2 (C=O), 143.3 ($^{\text{O}}\text{Tp-C5}$), 143.0 ($^{\text{Im}}\text{Tp-C3}$), 139.7 (Im), 139.5 ($^{\text{Im}}\text{Tp-C5}$), 137.1 ($^{\text{CO}}\text{Tp-C5}$), 136.7 ($^{\text{CO}}\text{Tp-C3}$), 135.2 ($^{\text{O}}\text{Tp-C3}$), 129.6 (C3), 129.4 (Im), 126.7 (C2), 122.6 (Im), 107.0 ($^{\text{CO}}\text{Tp-C4}$), 106.8 ($^{\text{O}}\text{Tp-C4}$), 106.5 ($^{\text{Im}}\text{Tp-C4}$), 82.5 (quaternary), 58.6 (CH_2OCH_3), 58.4 (CH_2OCH_3), 53.1 (COOCH_3), 52.1 (CH_2OCH_3), 49.0 (C5), 48.9 (C6), 48.7 (MeIm), 40.8 (C1), 34.6 (C4), 23.1 (gem Me), 22.2 (gem Me).

Diastereomer **3B** ($R_f = 0.24$, 34 mg, 27%) CV $E_{p,a} = 211$ mV (NHE). IR (HATR, glaze): $\nu_{\text{BH}} = 2476$ cm^{-1} , $\nu_{\text{CO}} = 1786$, 1723 cm^{-1} . ^1H NMR (500 MHz) (acetonitrile- d_3): δ 7.92 (1H, d, $J = 2.2$, $^{\text{O}}\text{Tp-H5}$), 7.83 (1H, d, $J = 1.9$, $^{\text{CO}}\text{Tp-H5}$), 7.76 (1H, d, $J = 2.2$, $^{\text{O}}\text{Tp-H3}$), 7.73 (1H, d, $J = 1.2$, $^{\text{CO}}\text{Tp-H3}$), 7.67 (1H, d, $J = 1.9$, $^{\text{Im}}\text{Tp-H5}$), 7.63 (1H, m, Im), 7.41 (1H, d, $J = 1.6$, $^{\text{Im}}\text{Tp-H3}$), 6.85 (1H, dd, $J = 1.6$, 1.6, Im), 6.80 (1H, dd, $J = 1.6$, 1.6, Im), 6.37 (1H, dd, $J = 2.2$, 2.2, $^{\text{CO}}\text{Tp-H4}$), 6.21 (1H, dd, $J = 2.2$, 2.2, $^{\text{O}}\text{Tp-H4}$), 6.05 (1H, dd, $J = 1.9$, 1.9, $^{\text{Im}}\text{Tp-H4}$), 5.71 (1H, m, H2), 5.53 (1H, m, H3), 3.64 (3H, s, COOCH_3), 3.49 (1H, m, H4), 3.29 (1H, dd, $J = 9.3$, 7.0, CH_2OCH_3), 3.17 (3H, s, MeIm), 3.13 (1H, dd, $J = 9.3$, 2.6, CH_2OCH_3), 3.08 (3H, s, CH_2OCH_3), 2.89 (1H, m, H1), 2.42 (1H, d, $J = 9.9$, H6), 1.73 (1H, dd, $J = 9.9$, 1.6, H5), 1.10 (3H, s, gem Me), 0.91 (3H, s, gem Me). ^{13}C NMR (125 MHz): δ 199.2 (C=O), 179.0 (C=O), 145.6 ($^{\text{O}}\text{Tp-C5}$), 142.9 ($^{\text{Im}}\text{Tp-C3}$), 141.8 ($^{\text{CO}}\text{Tp-C3}$), 139.3 ($^{\text{Im}}\text{Tp-C5}$), 137.0 ($^{\text{O}}\text{Tp-C5}$), 136.5 ($^{\text{CO}}\text{Tp-C5}$), 135.3 (Im), 132.0 (Im), 129.8 (C2), 126.1 (C3), 122.4 (Im), 106.9 ($^{\text{CO}}\text{Tp-C4}$), 106.7 ($^{\text{O}}\text{Tp-C4}$), 106.4 ($^{\text{Im}}\text{Tp-C4}$), 56.6 (CH_2OCH_3), 56.5 (COOCH_3), 52.1 (CH_2OCH_3), 49.5 (CH_2OCH_3), 47.3 (C6), 47.2 (C5), 41.1 (C4), 41.3 (MeIm), 34.6 (C1), 23.0 (gem Me), 22.9 (gem Me).

2-Methyl-2-[4-(3-oxobutyl)cyclohexa-2,5-dienyl]propionic Acid Methyl Acid (5). $R_f = 0.42$. Yield: 76%. ^1H NMR (300 MHz, CDCl_3): δ 5.63 (4H, m, H2,3,5,6), 3.70 (3H, s, OMe), 3.13 (1H, m, H4), 2.77 (1H, m, H1), 2.44 (2H, m, CHCH_2CH_2), 2.13 (3H, s, COMe), 1.71 (2H, m, $\text{CH}_2\text{CH}_2\text{CO}$), 1.14 (6H, s, gem Me). ^{13}C NMR (75 MHz, CDCl_3): δ 178.1 (CO), 130.8, 125.7 (CH), 52.0 (CH_3), 45.8 (quaternary), 43.0 (CH), 40.7 (CH_2), 30.1 (CH_3), 29.6 (CH_2), 22.5 (2 \times CH_3). Carbonyl resonance for the ketone was not observed. HRMS. Calcd. for $\text{C}_{15}\text{H}_{23}\text{O}_3^+$: 251.1647. Found: 251.1647. Purity (^1H NMR): $>90\%$.

2-(4-(Methoxymethyl)cyclohexa-2,5-dienyl)malonic Acid Dimethyl Ester (8). $R_f = 0.25$. For further purification, 20% EtOAc in hexanes was used. $R_f = 0.42$. yield 56%. ^1H NMR (300 MHz, CDCl_3): δ 5.77 (4H, m, H2, 3, 5, 6), 3.73 (6H, s, COOCH_3), 3.54 (1H, m, H4), 3.36 (1H, d, $J = 8.8$, COCHCO), 3.34 (3H, s, CH_2OCH_3), 3.29 (2H, d, $J = 6.6$, $\text{CHCH}_2\text{OCH}_3$), 2.97 (1H, m, H1). ^{13}C NMR (75 MHz, CDCl_3): δ 168.5 (CO), 128.7 (CH), 126.4 (CH), 77.1 (CH_2), 59.2 (CH), 57.8 (CH_3), 52.6 (2 \times CH_3), 37.1 (CH), 36.2 (CH). HRMS. Calcd for $\text{C}_{13}\text{H}_{19}\text{O}_5^+$: 255.1233. Found: 255.1233. Purity (^1H NMR): $>95\%$.

2-[4-(3-Oxybutyl)cyclohexa-2,5-dienyl]malonic Acid Dimethyl Ester (12). To a solution of **11** (50 mg, 0.086 mmol) in THF (0.5 g), MVK (9 mg, 0.13 mmol) was added and cooled to -78°C . A solution of TBSOTf (34 mg, 0.13 mmol) in THF (0.3 g) was also chilled and added to the above solution to react for 10 min, during which time, a solution of DBU (66 mg, 0.43 mmol) and dimethyl malonate (57 mg, 0.43 mmol) in THF (0.3 g) and a separate solution of $\text{Cu}(\text{OTf})_2$ (31 mg, 0.085 mmol) in THF (1.0 g) were also cooled to -78°C . The mixture of DBU and dimethyl malonate was then added to the reaction mixture immediately before the copper(II) solution was added. The reaction mixture was allowed to stand for 30 min at -78°C and then at 20°C for 15 min. Water (1.0 g) was added, and the reaction solution was transferred to a 75°C oil bath and allowed to sit for 1 h. The elution of 10% ethyl acetate in hexanes yielded the product as clear oil (6 mg, 25%, $R_f = 0.46$) after solvent evaporation. ^1H NMR (300 MHz, CDCl_3): δ 5.68 (m, 4H), 3.75 (s, 6H), 3.52 (dd, $J = 8.1$, 8.1, 1H), 3.33 (d, $J = 7.9$, 1H), 2.81 (m, 1H), 2.40 (t, $J = 8.1$, 8.1, 2H), 2.14 (s, 3H), 1.71 (m, 2H).

Conclusion

In all, four different d^6 transition metals (Os(II), Re(I), W(0), and Mo(0)) have been shown to promote tandem addition reactions with arenes. Of the heavy metals, the tungsten system $\{\text{TpW}(\text{NO})(\text{PMe}_3)\}$ appears to be the most electron-rich, reacting with electrophiles under the mildest conditions (lower acidity, weaker electrophiles). Somewhat less nucleophilic is the system $\{\text{TpRe}(\text{CO})(\text{MeIm})\}$, and the least activating of the

three heavy metal systems is $\{\text{Os}(\text{NH}_3)_5\}^{2+}$. In contrast, the osmium(II) system provides a benzenium complex that is most readily attacked by mild nucleophiles. The rhenium system is somewhat less electrophilic, and the tungsten system is seemingly inert to arenium addition unless addition of the nucleophile is accompanied by an increase in the metal oxidation state. These osmium(II)–benzenium complexes are also the most acidic, however, making their deprotonation at C4 a serious side reaction.⁵ The molybdenum system, while showing a capacity for arene activation with naphthalene, does not form a complex that with benzene sufficiently inert to allow its isolation. Taking these observations into account, the rhenium system $\{\text{TpRe-}$

$(\text{CO})(\text{MeIm})\}$ appears to be the best suited to promoting the target reaction of 1,4-dialkylation of benzene.

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Supporting Information Available: Proton and carbon NMR data. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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