Successive Activation and Perfunctionalization of Arenes by π-Complexation to $CpFe^+$ and Cp^*Ru^+ for the Construction of Organometallic Stars and Dendrimers

Beatriz Alonso,[†] Jean-Claude Blais,[‡] and Didier Astruc*,[†]

Laboratoire de Chimie Organique et Organométallique, UMR CNRS 5802, Université Bordeaux I, 33405 Talence Cedex, France, and Laboratoire de Chimie Structurale Organique et Biologique, EP CNRS No. 103, Université Paris VI, 4 Place Jussieu, 75252 Paris Cedex, France

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Summary: Temporary complexation and activation of hexamethylbenzene by $CpFe^+$ ($Cp = \eta^5$-C_5H_5) allow mild hexa-p-bromobenzylation. Then regioselective π-complexation of the six peripheral arene rings of the resulting star molecule by Cp^*Ru^+ ($Cp^* = \eta^5$-C_5Me_5) activates nucleophilic substitution of the six bromides by phenol dendrons to give an 18-allyl hexaruthenium dendrimer.

Introduction

Whereas organometallic activation of hydrocarbons and catalysis have provided a considerable advance in organic synthesis including aromatic transformations,[1] tandem-type reactions whereby two different metals are combined in successive reactions to reach sophisticated molecules have gained recent interest.[2] We would like to illustrate this principle here in metallodendrimer synthesis[3] starting from hexamethylbenzene, with two new versions of arene activation using π-complexation.

Results and Discussion

The first sequence involves the complexation of hexamethylbenzene to $CpFe^+$ giving $[FeCp(\eta^6\text{-}C_6Me_6)][PF_6]$, **1**,[4] followed by hexa-*p*-bromobenzylation (Scheme 1, step i).

The $CpFe^+$-induced hexabenzylation of hexamethylbenzene has been known for some time,[5] but extension to functional benzylbromides has been demonstrated so far only with alkoxy substituents.[5b] We now find that the hexabromobenzylation of **1** using *p*-Br-$C_6H_5CH_2Br$ and KOH in DME proceeds in large scale at 40 °C in 6 days with 80% yield, giving $[FeCp\{\eta^6\text{-}C_6(CH_2CH_2p\text{-}C_6H_4Br)_6\}][PF_6]$, **2** (Scheme 1), a yellow solid characterized inter alia by elemental analysis and its MALDI TOF mass spectrum (*m*/*z* 1297.76 $[M - PF_6]^+$, 100). This opens the route to divergent classic Pd-catalyzed functionalization.[6] To investigate the use of π-arene activation, however, we have envisaged the less classic complexation and activation of the peripheral bromobenzene rings by the CpM^+ group (M = Fe or Ru). The central iron group was first removed by photolysis with visible light in the presence of 0.95 equiv of PPh_3 in MeCN (1 day, Xenon lamp), giving an 84% yield of $C_6(CH_2CH_2p\text{-}C_6H_4Br)_6$, **3**, an off-white solid (step ii) characterized inter alia by elemental analysis and its MALDI TOF mass spectrum (*m*/*z* 1283.43, $[M + Ag]^+$, 100). Complexation of bromobenzene by $CpFe^+$ leads to some loss of bromide[4] and, thus, is inadequate. On the other hand, multiple complexation by Cp^*Ru^+ ($Cp^* = \eta^5$-C_5Me_5) proceeds regioselectively in the periphery in 72% yield by reaction with $[RuCp^*(CH_3CN)_3][OTf]$[7] in 2 h at reflux in CH_2Cl_2 to give the complex $[(RuCp^*)_6\{C_6(CH_2CH_2\eta^6\text{-}p\text{-}C_6H_4Br)_6\}][OTf]_6$, **4**, a tan solid (step iii of Scheme 1 and Figure 1). The hexaruthenium complex **4** was characterized by elemental analysis and by the prominent molecular peak at *m*/*z* 3339.89 corresponding to $[M - CF_3SO_3]^+$ (100) observed in the MALDI TOF mass spectrum. Complexation of the central hexasubstituted benzene ring is thus precluded by the large steric bulk of the star branches.

Activation of the nucleophilic substitution of halogens in the cationic complexes of the type $[MCp(C_6H_5X)][PF_6]$ (M = Fe or Ru) is well known.[4b] This nucleophilic activation has not yet been demonstrated for the less activating Cp^*Ru^+ fragment, however, although an example of activation of the substitution of fluoride by amine has been reported with Cp^*Fe^+,[8a] whose activating power is similar to that of Cp^*Ru^+.[8b] To show the use of this strategy in metallodendritic synthesis, we

[†] Université Bordeaux I.
[‡] Université Paris VI.

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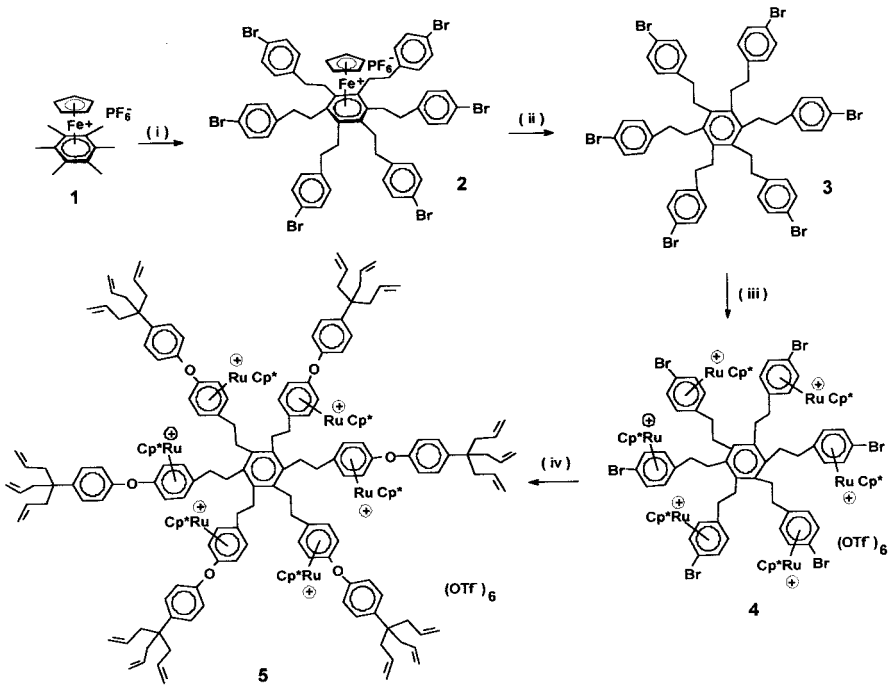
Scheme 1[a]



[a] (i) *p*-Br-$C_6H_5CH_2Br$, KOH, DME, 40 °C, 6 days, 80%; (ii) PPh_3 (0.95 equiv), MeCN, 1 day (Xe lamp), 84%; (iii) $[RuCp^*(CH_3CN)_3][OTf]$, 2 h, CH_2Cl_2, reflux, 72%; (iv) *p*-$HOC_6H_4C(CH_2CH{=}CH_2)_3$, K_2CO_3, DMF, 3 days, RT, 24%.

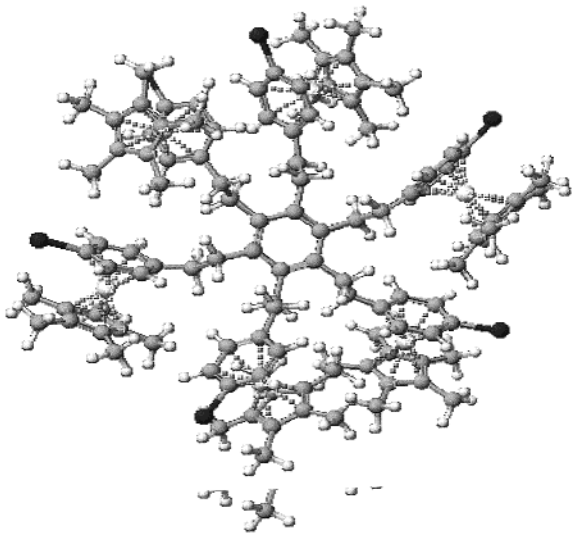


Figure 1. Molecular modeling calculations for **4** were carried out using CAChe. The optimized geometry was calculated with MM2 using augmented MM3 parameters to an average gradient less than 1. The conformation with minimized energy was obtained from the optimized molecule using the sequential search option in the software package. The Ru−Cp* distances were found to be the same as in known crystal structures containing this fragment.[7]

choose to continue the divergent dendritic construction with the phenol triallyl dendron *p*-$HOC_6H_4C(CH_2CH{=}CH_2)_3$.[8c] Reaction of the complex **4** with the dendron *p*-$HOC_6H_4C(CH_2CH{=}CH_2)_3$ in DMF in the presence of K_2CO_3 for 3 days at room temperature gives (24%) hexaruthenium 18-allylmetallodendrimer $[(RuCp^*)_6C_6\{CH_2\text{-}CH_2\text{-}\eta^6\text{-}p\text{-}C_6H_4OC_6H_4C(CH_2CH{=}CH_2)_3\}_6][OTf]_6$, **5**, as a tan powder (step iv). The MALDI TOF mass spectrum of **5** shows a prominent molecular peak at *m*/*z* (%) 4224.30 ($[M - CF_3SO_3]^+$, 100). and the ^1H and ^{13}C NMR data confirm its purity at the NMR accuracy. In an attempt to introduce larger phenol dendrons using this nucleophilic reaction, the molecular weight of the metallodendrimer reached around 10^4 amu; however, such larger dendrons could not be introduced in all six peripheral phenyl rings despite forcing conditions. This confirms the potential limit of the convergent strategy with large dendrons via this procedure.[9] On the other hand, the present sequential activation of a simple arene shows that sophisticated metallodendrimers can be cleanly synthesized using a divergent synthesis.

In conclusion, we have found a useful hexafunctionalization[10] of hexamethylbenzene and efficiently combined the enhanced acidity and nucleophilic activation of arenes provided by the π-complexation to the isolobal 12-electron $CpFe^+$ and Cp^*Ru^+ fragments, respectively, for a new regioselective metallodendritic synthesis.

Experimental Section

All reactions were carried out under an atmosphere of nitrogen by means of conventional Schlenk techniques. Dimethoxy-1,2-ethane (DME), tetrahydrofuran (THF), and diethyl ether were distilled from sodium/benzophenone. 1,2,3,4,5-Pentamethylcyclopentadiene, silver trifluoromethanesulfonate, K_2CO_3, copper(I) cyanide, lithium chloride, granular zinc, 1,2-dibromoethane, and chlorodimethylsilane were purchased from Aldrich and used as received. Chlorotrimethylsilane (Janssen Chimica) was distilled prior to use. 4-Bromobenzylbromide and lithium triethylborohydride (1.0 M

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solution in THF) were purchased from Aldrich and used as received. Ruthenium(III) chloride hydrate and 4-*tert*-butylphenol available from Janssen Chimica were used as received. Silica gel 60 (70−230 mesh) was used for column chromatographic purifications. The compounds $[FeCp(C_6Me_6)][PF_6]$,[5a] $[Cp^*Ru(CH_3CN)_3]^+OTf^-$,[7] and *p*-$OHC_6H_4C(CH_2CH{=}CH_2)_3$[8c] were prepared according to literature procedures. NMR spectra were recorded on a Bruker-AC 200 (^1H, 200 MHz; ^{13}C, 50.3 MHz) spectrometer or a Bruker-AC 250 (^1H, 250 MHz; ^{13}C, 62.9 MHz) spectrometer. Chemical shifts are reported in parts per million (δ) with reference to internal tetramethylsilane, $SiMe_4$, or calibrated using referenced solvent signals. Elemental analyses were performed by the CNRS Center of Microanalyses at Vernaison, France.

Synthesis of [FeCp{$C_6(CH_2CH_2C_6H_4Br)_6$}][PF_6] (2). $[FeCp(C_6Me_6)][PF_6]$ (3.00 g, 7.1 mmol) and 35.40 g (630.0 mmol) of finely divided KOH were stirred together under vacuum at 40 °C for 3 h, and then an inert atmosphere was maintained. A solution of 4-bromobenzyl bromide (31.50 g, 126.0 mmol) in 200 mL of freshly distilled DME was introduced by cannula. The resulting suspension was maintained under nitrogen at 40 °C for 156 h in the dark. The solvent was then removed under vacuum, and the brownish mixture was treated with CH_2Cl_2 (200 mL). The product, which precipitated as a pale orange solid, was collected by filtration, washed several times with water and diethyl ether, and dried in vacuo. Yield: 8.00 g (80%). Anal. Calcd for $C_{59}H_{53}FeBr_6PF_6$: C, 49.13; H, 3.70. Found: C, 48.93; H, 3.77. ^1H NMR (DMSO-d_6, 250 MHz): δ 3.07 and 3.32 (br m, 12H, CH_2), 5.09 (s, 5H, C_5H_5), 7.24 (d, 12H, C_6H_4), 7.58 (d, 12H, C_6H_4). ^{13}C NMR (DMSO-d_6, 62.9 MHz): δ 31.05 and 36.12 (*C*H_2), 79.60 (C_5H_5), 103.66 (C_6R_6), 120.80 (Ar*C*Br), 130.34 (C_6H_4), 131.44 (C_6H_4), 140.91 (Ar*C*H). MS (MALDI-TOF; *m*/*z* (%)): 1297.76 ([M − PF_6]$^+$, 100).

Synthesis of $C_6(CH_2CH_2C_6H_4Br)_6$ (3). Compound **2** (1.00 g, 0.7 mmol) and 0.95 equiv of triphenylphosphine is photolyzed in 300 mL of CH_3CN using intense visible light (Xenon lamp) for 24 h. The resulting off-white solid was isolated by filtration and washed with two 10 mL portions of CH_3CN and two 10 mL portions of diethyl ether and dried in vacuo. Yield: 0.70 g (84%). Anal. Calcd for $C_{54}H_{48}Br_6$: C, 55.13; H, 4.11. Found: C, 54.46; H, 3.95. ^1H NMR ($CDCl_3$, 250 MHz): δ 2.79 and 2.89 (br m, 12H, CH_2), 7.04 (d, 12H, C_6H_4), 7.47 (d, 12H, C_6H_4). ^{13}C NMR ($CDCl_3$, 62.9 MHz): δ 33.05 and 36.02 (*C*H_2), 120.08 (Ar*C*Br), 129.8 (C_6H_4), 131.8 (C_6H_4), 136.0 (C_6R_6), 140.7 (Ar*C*H). MS (MALDI-TOF; *m*/*z* (%)): 1283.43 ([M + Ag]$^+$, 100).

Synthesis of {$[RuCp^*(CH_2CH_2C_6H_4Br)]_6C_6$}$^{6+}(OTf^-)_6$ (4). Compound **3** (0.10 g, 0.08 mmol) in CH_2Cl_2 (ca. 50 mL) was transferred to a reaction vessel containing 0.39 g (9 equiv, 0.76 mmol) of $[Cp^*Ru(CH_3CN)_3]OTf$ and equipped with a Teflon stopcock. The reaction mixture was heated for 2 h at 45 °C and then filtered through Celite. The filtrate was concentrated to about 1/6 of its original volume, and then diethyl ether was added (ca. 50 mL). The resulting tan precipitate was isolated by filtration and then washed with two 10 mL portions of diethyl ether to yield 0.21 g (72% yield) of the title compound. Anal. Calcd for $C_{120}H_{138}Br_{16}Ru_6F_{18}S_6O_{18}$: C, 41.31; H, 3.99. Found: C, 40.49; H, 4.10. ^1H NMR (DMSO-d_6, 250 MHz): δ 1.88 (s, 90H, CH_3), 2.42 and 2.74 (br m, 12H, CH_2), 5.84 (d, 12H, C_6H_4), 6.50 (d, 12H, C_6H_4). ^{13}C NMR (DMSO-d_6, 62.9 MHz): δ 9.45 (*C*H_3), 31.05 and 31.12 (*C*H_2), 87.26 (C_6H_4), 89.70 (Ar*C*Br), 90.57 (C_6H_4), 96.74 (C_5CH_3), 103.57 (Ar*C*CH_2), 120 (quartet corresponding to CF_3SO_3), 135.8 (C_6R_6). MS (MALDI-TOF; *m*/*z* (%)): 3339.89 ([M − CF_3SO_3]$^+$, 100).

Synthesis of {$[RuCp^*(CH_2CH_2C_6H_4OC_6H_4C(CH_2CH{=}CH_2)_3)]_6C_6$}$^{6+}(OTf^-)_6$ (5). Compound **4** (0.10 g, 0.03 mmol) and K_2CO_3 (0.05 g, 0.34 mmol) were introduced under an inert atmosphere into a flamed and deaerated Schlenk flask. Then, *p*-$OHC_6H_4C(CH_2CH{=}CH_2)_3$ (0.10 g, 0.43 mmol), dissolved in 15 mL of freshly distilled DMF, was added. The reaction mixture was stirred for 72 h at room temperature. DMF was removed under vacuum, CH_2Cl_2 was added (ca. 15 mL), and the mixture was then filtered through Celite. The resulting solution was washed with distilled water and dried over Na_2SO_4. After removal of the solvent, the product was purified by repeated reprecipitations from CH_2Cl_2/diethyl ether. The resulting tan precipitate was isolated by filtration to yield 0.03 g (24% yield) of the title compound. ^1H NMR ($CDCl_3$, 250 MHz): δ 1.92 (s, 90H, CH_3), 2.44 (d, 36H, CH_2CH=), 2.71 and 3.30 (br m, 12H, CH_2), 5.02 (m, 36H, =CH_2), 5.55 (m, 18H, C*H*=), 5.68 (d, 12H, C_6H_4), 6.16 (d, 12H, C_6H_4), 7.19 (d, 12H, C_6H_4), 7.32 (d, 12H, C_6H_4). ^{13}C NMR ($CDCl_3$, 62.9 MHz): δ 10.43 (*C*H_3), 34.05 and 34.12 (*C*H_2), 41.93 (*C*H_2CH=), 43.08 (*C*H=), 80.28 (C_6H_4), 87.11 (C_6H_4), 96.02 (C_5CH_3), 117.47 (Ar*C*CH_2), 117.83 (=*C*H_2), 118.52 (C_6H_4), 128.45 (C_6H_4), 134.31 (*C*H=), 134.60 (Ar*C*O), 136.8 (C_6R_6), 142.50 (Ar*C*C), 154.02 (Ar*C*O). MS (MALDI-TOF; *m*/*z* (%)): 4224.30 ([M − CF_3SO_3]$^+$, 100).

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