Preparation of Optically Pure Tricarbonylcyclohexadienyliron Complexes: Use of a Trifluoromethyl Group as a Regiodirector during Hydride Abstraction

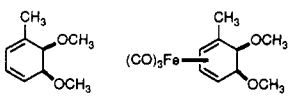
Anthony J. Pearson,*,† Ann M. Gelormini,† and A. Alan Pinkerton‡

Departments of Chemistry, Case Western Reserve University, Cleveland, Ohio 44106, and University of Toledo, Toledo, Ohio 43606

Received June 24, 1991

The reaction of optically pure 1-(trifluoromethyl)cyclohexa-1,3-diene-5,6-diol with $Fe_2(CO)_9$ proceeds stereospecifically to give the endo complex **4**, which was characterized by single-crystal X-ray structure determination; the trifluoromethyl group in **4** is found to be an excellent regiodirector during hydride abstraction and dehydroxylation reactions of **4**.

It has been observed that ester,[1] hydroxyl,[2a] and ether[2b] functional groups are capable of exerting stereodirecting effects during the attachment of a tricarbonyliron group to a cyclohexadiene, a property which might be useful for the preparation of optically pure complexes as intermediates for natural products synthesis. Stephenson has recently reported that the diether derivative **1** is converted exclusively to the *syn*-tricarbonyliron complex **2** in 53%

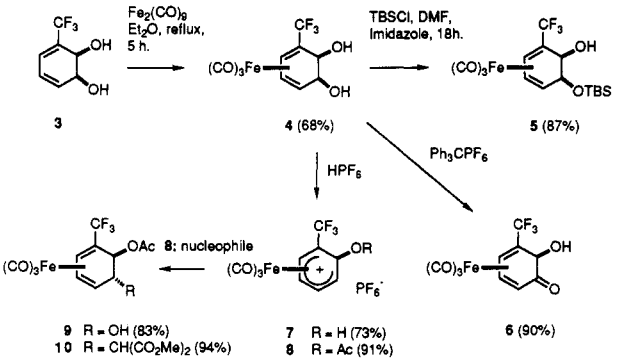


1 **2**

yield, although the stereochemical assignment was based only on NMR spectroscopic data and subsequent chemistry. Conversion of **2** to dienyl complexes was accomplished by removal of one MeO group using $Ph_3C^+BF_4^-$, but complete regiocontrol was not possible, owing to the fact that a methyl substituent is a rather poor director in these reactions, since it only weakly perturbs the electronic configuration of the complexed dienyl system in the product. Cyclohexadienediols are readily available in optically pure form via microbial oxidation of the corresponding benzene derivative,[3] and so it should be possible to fine-tune the diene to dienyl conversion by appropriate choice of substituent. We report herein our own work using the (trifluoromethyl)cyclohexadienediol **3** in optically pure form ($[\alpha]^{20}_D$ −62°, *c* 1.97, CH_3OH). We anticipated that the electron-withdrawing CF_3 group would show directing effects similar to that known for esters,[1] and this study represents the first example of such effects. We also report X-ray crystallographic confirmation that hydroxy groups direct cis during complexation.

Treatment of **3** with $Fe_2(CO)_9$ in refluxing ether gave a single complex (>95% as judged by ^1H NMR of the *crude* product). Recrystallization from 1:10 ethyl acetate/hexane afforded pure crystalline material, in 68% yield, which was shown to have the endo stereochemistry **4** by single-crystal X-ray structure determination (Figure 1). The absolute stereochemistry of **4**, and therefore the diol **3** was confirmed by the *R* factor test (see Experimental Section).

The expected difference in steric environment of the hydroxy groups in complex **4** was readily demonstrated by its clean conversion to the monoprotected derivative **5**. Of greater interest, however, was the observation that treatment of **4** with $Ph_3C^+PF_6^-$ (CH_2Cl_2, 0 °C, 4 h) afforded directly the dienone complex **6**, in 90% yield, the structure



of which was readily assigned by ^1H NMR spectroscopy. No other product was detected. This result contrasts with the analogous reaction on complex **2**, which gives mainly the product of demethoxylation. Presumably, the combined effects of the CF_3 and O*H* groups (compared to *Me*, O*Me* used in ref 2) lead to a preference for *hydride* abstraction, which is completely regioselective. That this regiocontrol is not entirely due to steric hindrance from the CF_3 group, preventing hydride abstraction from C6, is indicated by the following experiment.

Treatment of complex **4** with hexafluorophosphoric acid in dichloromethane (0 °C, 2 h) followed by addition of diethyl ether gave a single ether-insoluble dienyl complex in 73% yield, readily assigned the structure **7** by ^1H NMR spectroscopy. When this reaction was conducted in the presence of excess acetic anhydride, the acetyl-protected dienyl complex **8** was obtained in 91% yield. Complex **8** is very moisture sensitive and readily gives the diene complex **9** in 83% yield on treatment with water. Treatment of **8** with $NaCH(CO_2Me)_2$ gave the expected malonate adduct **10** in 94% yield.

Thus, we have confirmed the ability of hydroxy substituents to act as stereodirectors during complexation of

† Case Western Reserve University.
‡ University of Toledo.

(1) Birch, A. J.; Williamson, D. H. *J. Chem. Soc., Perkin Trans. 1* **1973**, 1892.

(2) (a) Howard, P. W.; Stephenson, G. R.; Taylor, S. C. *J. Organomet. Chem.* **1989**, *370*, 97. Stephenson, G. R.; Howard, P. W.; Taylor, S. C. *J. Chem. Soc., Chem. Commun.* **1991**, 127. (b) Howard, P. W.; Stephenson, G. R.; Taylor, S. C. *J. Chem. Soc., Chem. Commun.* **1990**, 1182; **1988**; 1603.

(3) For representative examples, see: Ziffer, H.; Jerina, D. M.; Gibson, D. T.; Kobal, V. M. *J. Am. Chem. Soc.*, **1973**, *95*, 4048. Gibson, D. T.; Gschwendt, B.; Yeh, W. K.; Kobal, V. M. *Biochemistry* **1973**, *12*, 1520. Schofield, J. A. European Patent Application EP 252567; *Chem. Abstr.* **1988**, *108*, 203317e. Pittol, C. A.; Pryce, R. J.; Roberts, S. M.; Ryback, G.; Sik, V.; Williams, J. O. *J. Chem. Soc., Perkin Trans. 1* **1989**, 1160. For a recent method for assignment of optical purity and absolute stereochemistry, see: Boyd, D. R.; Dorrity, M. R. J.; Hand, M. V.; Malone, J. F.; Sharma, N. D.; Dalton, H.; Gray, D. J.; Sheldrake, G. N. *J. Am. Chem. Soc.* **1991**, *113*, 666.

0276-7333/92/2311-0936$03.00/0

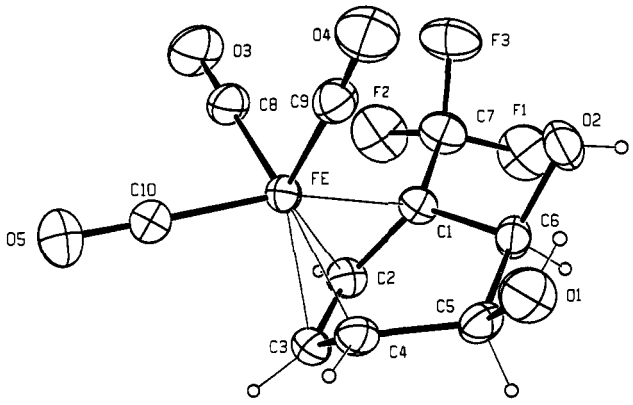
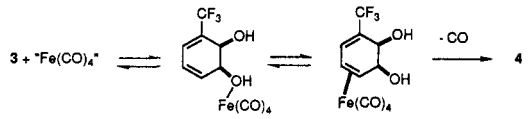


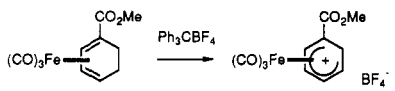
Figure 1. X-ray crystal structure of complex 4 showing 30% probability ellipsoids. Selected bond lengths (Å): C1–C2 = 1.422 (4); C1–C6 = 1.516 (4); C2–C3 = 1.393 (4); C3–C4 = 1.408 (4); C4–C5 = 1.493 (4).

Scheme I. Possible Mechanism Showing OH-Directed Complexation of 3



a neighboring 1,3-diene, and we have introduced a new group, CF_3, as a regiodirector for hydride abstraction and related reactions. Presumably, the stereodirecting effect is due to initial coordination of the reactive $Fe(CO)_4$ complex, generated by cleavage of $Fe_2(CO)_9$, to an OH (or OMe) group, followed by transfer to the olefinic group as outlined in Scheme I. Such directing effects are not unknown for reactions involving metal carbonyls, a particularly well-known example being the stereoselective hydroxylation of allylic alcohols catalyzed by molybdenum hexacarbonyl.[4]

The regioselective hydride abstraction and acid-promoted conversion to dienyl complexes observed here parallel the known reaction of ester complex 11, which is converted predominantly to 12 on treatment with triphenylmethyl cation.[1] This has been explained on the



11 12

basis of MO calculations as being due to the preferred formation of the dienyl cation that has the higher HOMO and lower LUMO energy levels, leading to a stronger synergistic interaction with the iron d orbitals.[5] Similar perturbation effects are expected for inductively electron-withdrawing groups, as is confirmed by the present study.

Experimental Section

All reactions were conducted under an atmosphere of dry nitrogen, using flame-dried glassware. Ether and tetrahydrofuran were distilled from sodium and benzophenone; methylene chloride and acetonitrile were distilled from calcium hydride. Infrared spectra were recorded for solutions in CCl_4, unless otherwise specified, using a Perkin-Elmer 1600 series FT-IR spectrophotometer. Melting points were determined using a Thomas Hoover apparatus and are uncorrected. ^1H NMR spectra were recorded using a Varian XL-200H spectrometer, ^{13}C NMR spectra were recorded with a Varian Gemini 300 spectrometer, and mass spectra were determined in-house using a Kratos MS25A instrument. Optical rotations were measured using a Perkin-Elmer 241 digital polarimeter, in methanol solution unless otherwise noted. Combustion analyses were determined by Galbraith Laboratories, Knoxville, TN. The optically pure diol 3 was obtained as a gift from Dr. R. J. Pryce of Shell Research (U.K.).[6]

Tricarbonyl[1-(trifluoromethyl)cyclohexa-1,3-diene-5,6-diol]iron (4). Nonacarbonyldiiron (3.0 g, 8.33 mmol) was stirred in diethyl ether (11 mL) for 10 min, and diol 3 (500 mg, 2.78 mmol) dissolved in the minimum volume of ether was added via syringe. Stirring was continued at reflux temperature for 5 h, the cooled reaction mixture was filtered through Celite, and the pad was washed with ether. The combined filtrate was evaporated under reduced pressure, and the residue was chromatographed on silica gel (1:1 EtOAc/hexanes, R_f = 0.4). Recrystallization of the product (10% EtOAc in hexanes) afforded pure complex 4 (604 mg, 68%): mp 114–115 °C; $[\alpha]^{21}_D$ +62° (*c* 1.02); IR ($CHCl_3$) 3615, 2071, 2010 cm^{-1}; ^1H NMR ($CDCl_3$) δ 2.83 (1 H, d, *J* = 6.1 Hz), 2.95 (1 H, d, *J* = 4.6 Hz), 3.20 (1 H, dd, *J* = 6.7, 2.0 Hz), 3.86 (2 H, m), 5.18 (1 H, dd, *J* = 6.7, 4.6 Hz), 5.78 (1 H, dd, *J* = 4.6, 1.6 Hz); ^{13}C NMR (proton decoupled) 129.4 (q, *J* = 275 Hz, CF_3), 84.2, 84.1, 81.2, 67.5, 67.0, 66.7; HRMS calcd for $C_{10}H_7F_3FeO_5$ 319.9595, found 319.9579. Anal. Calcd: C, 37.53; H, 2.20. Found: C, 37.34; H, 2.27.

Tricarbonyl[5-[(*tert*-butyldimethylsilyl)oxy]-1-(trifluoromethyl)cyclohexa-1,3-dien-6-ol]iron (5). Complex 4 (50 mg, 0.156 mmol) was dissolved in DMF (1 mL) containing imidazole (12.7 mg, 0.187 mmol) and Bu^tMe_2SiCl (46.9 mg, 0.312 mmol). The reaction mixture was stirred at room temperature for 20 h, after which time it was quenched with water (2 mL) and the product extracted into ether (3 × 10 mL), dried over $MgSO_4$, and purified by chromatography (2:3 ethyl acetate/hexane, R_f = 0.5) to give light yellow crystals (59 mg, 87% yield): mp 112–113 °C; $[\alpha]^{22}_D$ +99° (*c* 0.73, MeOH); IR 3691, 2069, 2014 cm^{-1}; ^1H NMR ($CDCl_3$) δ 0.09 (3 H, s), 0.15 (3 H, s), 0.93 (9 H, s), 3.04 (1 H, dd, *J* = 6.1, 4.8 Hz), 3.34 (1 H, d, *J* = 6.2 Hz), 3.79 (1 H, d, *J* = 6.2 Hz), 3.92 (1 H, ddq, *J* = 6.2, 6.1, J_F = 0.9 Hz), 5.15 (1 H, t, *J* = 4.8 Hz), 5.60 (1 H, dq, *J* = 4.7, J_F = 0.9 Hz). Anal. Calcd for $C_{16}H_{21}F_3FeO_5Si$: C, 44.23; H, 4.88. Found: C, 44.05; H, 4.93.

Tricarbonyl[6-hydroxy-1-(trifluoromethyl)-1,3-cyclohexadien-5-one]iron (6). Complex 4 (100 mg, 0.312 mmol) and Ph_3CPF_6 (145.3 mg, 1.2 equiv) were stirred in CH_2Cl_2 (5 mL) at 0 °C for 2 h. The reaction mixture was added dropwise to ether (20 mL), yielding no precipitate (no dienyl complex is formed). The solvent was removed under reduced pressure and the product purified by chromatography (1:1 ether/hexane, R_f = 0.4) to give yellow flakes (89 mg, 90% yield): mp 132–133 °C; $[\alpha]^{21}_D$ +326.8 (*c* 1.2); IR 3745, 2087, 2034, 2015, 1683 cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.30 (1 H, s), 3.41 (1 H, dd, *J* = 5.6, 1.8 Hz), 3.88 (1 H, s), 5.92 (2 H, m); HRMS calcd for $C_{10}H_5F_3FeO_5$ 317.9438, found 317.9468. Anal. Calcd: C, 37.77; H, 1.58. Found: C, 37.83; H, 1.79.

Tricarbonyl[6-hydroxy-1-(trifluoromethyl)cyclohexadienyl]iron Hexafluorophosphate (7). Complex 4 (100 mg, 0.304 mmol) was dissolved in CH_2Cl_2 (2 mL), containing HPF_6 (133 μL, 40% water by weight) and acetic anhydride (330 μL, 1.1 equiv/water) to act as a desiccant. A pale yellow precipitate formed instantly. The remainder of the product was driven out of solution by addition of ether and the product was isolated by Craig tube crystallization (89 mg, 73%): IR (Nujol) 2134, 2107, 2081 cm^{-1}; ^1H NMR (CD_3CN) δ 4.56 (1 H, d, *J* = 7.9 Hz), 5.25 (1 H, s), 6.29 (1 H, tt, *J* = 8.1, 5.0 Hz), 6.57 (1 H, d, *J* = 5.0 Hz), 7.55 (1 H, t, *J* = 5.1 Hz). Anal. Calcd for $C_{10}H_6F_9FeO_4P$: C, 26.81; H, 1.35. Found: C, 27.41; H, 1.47.

Tricarbonyl[6-acetoxy-1-(trifluoromethyl)cyclohexadienyl]iron Hexafluorophosphate (8). Complex 4 (350 mg, 1.10 mmol) was dissolved in a mixture of acetic anhydride (1 mL), CH_2Cl_2 (1 mL), and HPF_6 (384 μL of 60% aqueous solution) and was allowed to stir at 0 °C for 2 h, additional acetic anhydride being added as necessary to keep the product in solution (approximately 1.5 mL). An additional 2 mL of CH_2Cl_2 was added.

(4) Sharpless, K. B.; Michaelson, R. C. *J. Am. Chem. Soc.* **1973**, *95*, 6136. Carlson, R. G.; Behn, N. S. *J. Org. Chem.* **1967**, *32*, 1363.

(5) Pearson, A. J. *Transition Met. Chem.* **1981**, *6*, 67. Eisenstein, O.; Butler, W.; Pearson, A. J. *Organometallics* **1984**, *3*, 1150.

(6) For the preparation of 3 see: Schofield, J. A. European Patent Application EP 252,568; *Chem. Abstr.* **1989**, *110*, 37806h.

The product was isolated by adding the solution dropwise to ether (20 mL), decanting the solvent, rinsing the residue by decantation with ether, and recrystallizing from freshly distilled acetonitrile and ether (432 mg, 91% yield): IR (Nujol) 2133, 2097, 2086, 1762 cm^{-1}; ^1H NMR (CD_3CN, 0 °C) δ 2.19 (3 H, s), 4.47 (1 H, d, J = 7.6 Hz), 5.19 (1 H, s), 5.98 (1 H, dd, J = 7.6, 5.9 Hz), 6.56 (1 H, d, J = 6.1 Hz), 7.15 (1 H, dd, J = 6.1, 5.9 Hz). This compound was extremely moisture sensitive, and satisfactory combustion analysis was not obtained.

Tricarbonyl[6-acetoxy-5-hydroxy-1-(trifluoromethyl)-cyclohexadiene]iron (9). The dienyl salt (8) (100 mg, 0.205 mmol) was dissolved in acetonitrile (2 mL) at 0 °C. This was added dropwise, with stirring to water, buffered with $NaHCO_3$ (1.5 mL), and the mixture was allowed to warm to room temperature. Ether extraction in the usual way, followed by purification by flash chromatography (1:1 ethyl acetate/hexane, R_f = 0.4), gave yellow crystals (69 mg, 83% yield): mp 100–101 °C; $[\alpha]^{23}_D$ −47.0° (c 0.65); IR 3363, 2073, 2006, 1740 cm^{-1}; ^1H NMR ($CDCl_3$) δ 2.12 (3 H, s), 3.16 (2 H, m becomes 1 H, dd J = 5.2, 3.7 Hz after D_2O shake), 3.92 (1 H, d, J = 3.8 Hz), 4.40 (1 H, s), 5.50 (1 H, t, J = 5.4 Hz), 5.82 (1 H, dq, J = 5.3, J_F = 0.7 Hz). Anal. Calcd for $C_{12}H_9F_3FeO_6$: C, 39.78; H, 2.51. Found: C, 39.85; H, 2.73.

Tricarbonyl[dimethyl [2-5-η-6-acetoxy-5-(trifluoromethyl)cyclohexa-2,4-dienyl]malonate]iron (10). Sodium hydride (64 mg of 50% dispersion in mineral oil) was rinsed with hexane and THF at 0 °C. Tetrahydrofuran (4 mL) and dimethyl malonate (200 mg) were added, and the mixture was stirred for 15 min. A 1-mL aliquot of this solution was added via syringe to a stirred suspension of 8 (100 mg, 0.206 mmol). The mixture was stirred at room temperature for 30 min, water (2 mL) was added, and the product was extracted with ether in the usual way. Chromatography on silica gel (25% ether in hexane, R_f = 0.1) afforded 10 as a yellow oil (89 mg, 94% yield): $[\alpha]^{23}_D$ −93.0° (c 1.12); IR 2073, 2013, 1734 cm^{-1}; ^1H NMR ($CDCl_3$) δ 2.04 (3 H, s), 2.60 (1 H, m), 3.30 (1 H, ddd, J = 5.5, 3.6, 1.8 Hz), 3.74 (3 H, s), 3.76 (3 H, s), 3.80 (1 H, d, J = 5.5 Hz, obscured), 4.97 (1 H, d, J = 1.8 Hz), 5.30 (1 H, dd, J = 5.5, 4.5 Hz) 5.63 (1 H, dq, J = 4.5, J_F = 0.7 Hz); ^{13}C NMR ($CDCl_3$) δ 207.9, 169.8, 168.2, 168.0, 125.9 (q, J_F = 270 Hz, CF_3), 83.9, 83.2, 70.8, 59.1, 58.9, 55.6, 52.7, 49.0, 47.9, 20.8.

Crystal Data for Compound 4: $C_{10}H_7FeF_3O_5$, monoclinic, space group $P2_1$ (No. 4), a = 6.915 (1) Å, b = 7.889 (1) Å, c = 10.891 (2) Å, β = 95.44 (1)°, V = 591.5 Å^3. For Z = 2 and fw = 320.01 the calculated density is 1.80 g/cm^3. Using an Enraf-Nonius CAD4 diffractometer, Mo Kα (λ = 0.709 30 Å) radiation, a total of 2529 reflections were collected, of which 2333 were unique. The structure was solved by direct methods. A total of nine atoms were located from the first E-map and the remaining atoms found in succeeding difference Fourier syntheses. Hydrogen atoms were located, and their positions and isotropic thermal parameters were refined. The structure was refined in full-matrix least squares on F (R factor 0.030). The absolute configuration was confirmed by the R factor test (R(enantiomer) = 0.041). Atomic coordinates, bond lengths and angles, and thermal parameters are available as supplementary material.

Acknowledgment. We are grateful to the National Science Foundation for financial support (Grant CHE 8921944 and Research Experience for Undergraduates Grant CHE 8804605) and to Dr. R. J. Pryce of Shell Research (U.K.) Ltd., for generous gifts of (trifluoromethyl)cyclohexadienediol (3).

Registry No. 3, 131101-28-5; 4, 138061-94-6; 5, 138061-95-7; 6, 138061-96-8; 7, 138061-98-0; 8, 138062-00-7; 9, 138062-01-8; 10, 138062-02-9; nonacarbonyldiiron, 15321-51-4; dimethyl malonate, 108-59-8.

Supplementary Material Available: Complete structural report for complex 4 including tables of positional and thermal parameters, general temperature factor expressions, bond distances, bond angles, and intensity data (11 pages). Ordering information is given on any current masthead page.

Functionalization of Metalated Cyclopentadienyl Ligands via Palladium-Catalyzed Cross-Coupling Reactions

E. C. Brehm, J. K. Stille,† and A. I. Meyers*

Department of Chemistry, Colorado State University, Fort Collins, Colorado 80523

Received June 19, 1991

The palladium-catalyzed coupling reaction between tricarbonyl(iodo-η^5-cyclopentadienyl)methyltungsten and various alkynyl-, aryl-, and vinylstannanes yields the corresponding coupled derivatives. The three classes of tin coupling partners were represented by (2-phenyl-1-ethynyl)trimethylstannane, 1-propynyltrimethylstannane, and 1-hexynyltri-*n*-butylstannane; phenyltri-*n*-butylstannane, and (4-methylphenyl)trimethylstannane; and (*Z*)-methyl 3-(tributylstannyl)acrylate, trimethylvinylstannane, and [2-(trimethylsilyl)-1(*E*)-ethenyl]trimethylstannane. This chemistry demonstrates a new, general route for the formation of a variety of functionally substituted η^5-cyclopentadienyl transition-metal compounds, whereby the cyclopentadienyl ring can be derivatized by several classes of organostannane reagents without affecting the other ligands on the transition metal.

Introduction

There are few general routes in the literature for the functionalization of metalated η^5-cyclopentadienyl half-sandwich complexes. Historically much study has been directed in this area due to certain aromatic-type electrophilic substitutions demonstrated by ferrocene. The products resulting from substitution on ferrocene often have unique chemical and physical properties.[1] Despite the successes of the ferrocene-based cases, few other η^5-cyclopentadienyl transition-metal complexes have undergone similar aromatic-type substitutions. The reason that most η^5-cyclopentadienyl metal complexes fail to undergo ring substitution is perhaps their inherent lack of aromatic character, or even more reasonable, more facile

* To whom all correspondence should be addressed.
† Deceased, July 19, 1989.

(1) (a) Hart, W. P.; Macomber, D. W.; Rausch, M. D. *J. Am. Chem. Soc.* **1980**, *102*, 1196. (b) Wright, M. E. *Organometallics* **1990**, *9*, 853.

0276-7333/92/2311-0938$03.00/0