Journal of Organometallic Chemistry, 370 (1989) 97–109
Elsevier Sequoia S.A., Lausanne – Printed in The Netherlands
JOM 09684

Transition metal mediated asymmetric synthesis

X *. Homochiral π-complexes with planar chirality: synthetic equivalents of chiral cyclohexadiene dications

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(Received November 3rd, 1988)

Abstract

Homochiral 6-methoxy-substituted dienyltricarbonyliron complexes have been obtained from 1-methylcyclohexa-1,3-diene-5,6-diol (available via microbial oxidation of toluene) by complexation and removal of an allylic substituent with acids or with triphenylcarbenium tetrafluoroborate. A variety of optically active tricarbonyliron complexes have been produced from these compounds. The optical purity of the product and the stereochemistry of the complexation reaction have been determined. The high efficiency of chirality transfer during complexation of 5,6-dimethoxy-substituted dienes makes this method suitable as a general route to resolved organoiron complexes

Transition metal π-complexes offer complete stereocontrol in their alkylation reactions. When the unsaturated organic ligand carries an unsymmetrical substitution pattern, the π-complexes derived from it have planar chirality. In these circumstances, stereocontrolled alkylation reactions provide efficient chirality transfer between the planar chirality of the organometallic moiety and chirality at carbon formed at the site of alkylation. By the use of stoichiometric metal complexes, the metal control centre can be retained in intermediates through a series of synthetic reactions. This offers an efficient approach to enantioselective synthesis in which the metal centre takes on a crucial role in the synthetic strategy, conferring stereocontrol throughout a reaction sequence [1].

In our studies of chiral organometallic π-complexes as synthetic intermediates of this type, it has been our objective to develop new methods for the repeated use of

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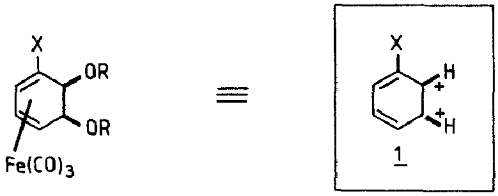
* For Part IX see ref. 5.

0022-328X/89/$03.50

the metal control centre. We have recently described target-oriented synthetic work [2] that employs this principle, and have reported investigations [3,4] aimed at the development of more general procedures for the multiple alkylation process. We have established [1,4] that 5,6-dioxygenation provides a pattern of reactivity equivalent to the dication synthon **1**. For enantioselective applications [1], convenient methods are needed for the general preparation of enantiomerically pure metal complexes. In this paper we describe progress towards this third objective which has led to the formation of a series of homochiral tricarbonyliron complexes which bear functionality suitable for use in repeated alkylation sequences. Part of this work has been the subject of a preliminary communication [5].



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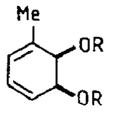
Results and discussion

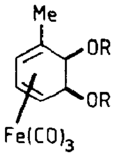
Synthesis of homochiral dienyl complexes

Complexation of chiral natural products has been exploited to prepare a number of optically active tricarbonyliron complexes [6,7]. To provide an efficient procedure, high diastereoselectivity is necessary in the complexation process, pointing to a requirement for powerful control groups arrayed near the site of complexation. The complexation of limonene [6], in which a 1-methylethenyl substituent directs the initial approach of an $Fe(CO)_4$ fragment, is typical of this type of reaction. Previously, the presence of control groups on substrate ligands has severely limited the potential applications of the homochiral complexes produced. Our approach to this problem has been to use the 5,6-dioxygenation available in microbially derived cyclohexa-1,3-diene-5,6-diols to control the complexation reaction. In this system, the control groups can subsequently be easily removed as a natural part of the further elaboration of the intermediates towards multiply alkylated organic products [4].

Microbial oxidation of toluene by *Pseudomonas putida* has been extensively investigated [8]. By use of mutant strains of the organism in which further biological degradation of the ring is blocked, it is possible to isolate the initial dioxygenated product **2a** in commercial quantities. Applying methods originally developed [4] for



2 a: R = H
b: R = Me
c: R = Ac
d: R = Et



3 a: R = H
b: R = Me
c: R = Ac
d: R = Et

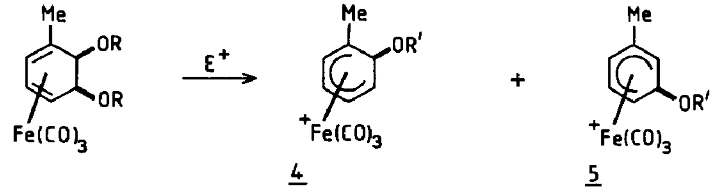


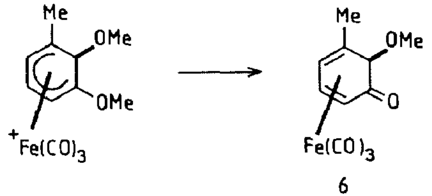
Table 1

Substrate / Reagent	Yield	Ratio 4 : 5	Product
R = Me E$^+$ = H$^+$	78 %	1 : 1	R' = Me b
R = Me E$^+$ = CPh$_3^+$	74 %	5 : 1	R' = Me b
R = H E$^+$ = H$^+$/Ac$_2$O	65 %	1 : 1	R' = Ac c
R = Et E$^+$ = H$^+$	73 %	2 : 3	R' = Et d
R = Et E$^+$ = CPh$_3^+$	72 %	1 : 1	R' = Et d
R = Ac E$^+$ = CPh$_3^+$	55 %	5 : 7	R' = Ac c

the stereocontrolled complexation of cyclohexa-1,3-diene-5,6-diol, obtained from benzene, we have converted **2a** into a mixture 6-*endo*-alkoxy substituted dienyl complexes **4b** and **5b** (Table 1) by methylation, complexation, and treatment with TFA to remove one of the alkoxy groups. As had been observed in the case the benzene-derived diol [4], the complexation proved to be completely stereocontrolled, forming a single diastereoisomer which was later shown to be the di-*endo* isomer **3b** (see below). Because of the unsymmetrical substitution pattern on the diene, regiocontrol in the demethoxylation step is an important consideration in the toluene series. When demethoxylation was performed in TFA, **4b** and **5b** were obtained as 1/1 mixture of the two regioisomers. The NMR spectra of **4b** and **5b** were readily distinguished by the marked difference in the resonances of the 1- and 2-methyl groups. The 1-methyl protons appeared as a broad singlet at 1.70 ppm whereas the 2-methyl protons resonated at 2.12 ppm. Both **4b** and **5b** displayed coupling patterns indicative of 6-*endo* substituted salts, i.e. a singlet for the 6-H proton [4].

A considerable improvement was achieved when a more bulky electrophile was employed. Reaction with triphenylcarbenium tetrafluoroborate selectively removed the less hindered of the two OMe groups to form **4b** as a 5/1 mixture with **5b**. Since the 1-methyl substituent on **4b** can be selectively deprotonated in base, the use of a chemical method for separation of this mixture was examined. Triethylamine was added to form a neutral η^4-triene complex, which was filtered through silica and re-protonated with TFA to afford **4b** > 97% pure in 46% recovery.

The removal of OMe by the triphenylcarbenium reagent is a notable result since the complex **3b** has hydrogens available for hydride abstraction from the exo face. Small and variable amounts of 1,6-dimethoxydienyl complexes were indeed formed in the these reactions, and could easily be removed by selective hydrolysis in the usual way [9]. Under different conditions, hydride removal was enhanced and the dienone complex **6** was obtained in 32% yield after hydrolysis. As expected, no products arose from hydride abstraction adjacent to the methyl group, and **6** was obtained as a single regioisomer. Attempted conversion of **6** into the cationic dienyl ketone **7** with TFA or triphenylcarbenium reagents was unsuccessful.



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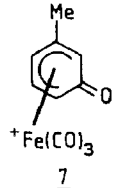

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Direct complexation of the diol **2a** has also been examined. Reaction with $Fe_2(CO)_9$, both by heating in ether and by the sonolysis method described by Ley [10], were unsatisfactory for this substrate. The required complex was obtained, however, when the diol and $Fe_2(CO)_9$ were stirred at room temperature in THF. Again, a single diastereoisomer was formed. This is taken to be the di-*endo* isomer **3a** on the basis of the comparison of CD spectra and the similarity of its method of preparation to that used for the ethers. The CD curves of tricarbonyliron complexes contain bands which are valuable in examination of the stereochemistry of attachment of the metal to the diene ligand [11]. CD curves for both **3a** and **3b** show maxima at about 300 nm, providing evidence for common relative stereochemistry in both cases. Had **3a** been the di-*exo* isomer, a band at 300 nm of the opposite sign would have been expected. Attempts to convert the diol **3a** into the diether **3b** with methyl iodide were unsuccessful, resulting in the formation (in < 5% yield) of traces of monoethers which were identified tentatively from their NMR spectra and were not characterised further. It seems most likely that the less hindered of the two alcohol groups was selectively alkylated.

In an attempt to form the alkoxy salts **4a** and **5a**, treatment of the diol **3a** with HPF_6 to remove an alcohol group, afforded, in 65% yield, a yellow powder which exhibited IR bands at 2118 and 2056 cm^{-1} (nujol mull), consistent with the expected products. This material proved unstable and was not examined further. Poor stability of 6-hydroxydienyl complexes has been reported previously [12]. Removal of OH by reaction with HBF_4 in acetic anhydride [13] proved a more acceptable procedure, converting **3a** directly into the *endo* acetoxy complexes **4c** and **5c** in 65% yield. The typical NMR coupling patterns observed for **4b** and **4c** again support the assignment of *endo* relative stereochemistry in **4c**, showing the characteristic singlet for H-6.

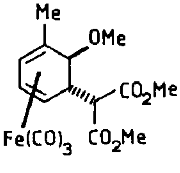
An authentic sample of the mixture of 6-acetoxydienyl complexes was obtained by acetylation of **2a** to form the diester **2c** in 43% yield. Complexation by the sonolysis method afforded the *endo* product **3c** (10% yield), which was converted in 55% yield into a 5 : 7 mixture of **4c** and **5c** by reaction with triphenylcarbenium hexafluorophosphate.

At this stage we had determined that the best prospect of regiocontrol arose from exploitation of steric differences between the two OR groups in the substrates **3**. Variation of the R group to improve regiocontrol was examined. The conversion of **2a** into the diethyl ether **2d** and complexation with $Fe_2(CO)_9$ in THF at room temperature afforded diether complex **3d**, again as a single stereoisomer, with a CD spectrum similar to the di-*endo* complexes obtained earlier. The diene complexes of type **3** consistently showed CD maxima at about 300 nm. The diethers **3b**,**3d** and the diacetate **3c** also showed minima at higher wavenumbers (350–360 nm). This band was missing in the CD curve of the diol **3a**.

Reaction with TFA produced a 2 : 3 mixture of products, slightly favouring the removal of the more hindered of the two ether groups. Increased selectivity for the formation of **5d**, seen when the ethyl ether is compared with this methyl ether, is consistent with steric control reflecting a greater release of strain by removal of the OEt group flanked by methyl and ether groups. A similar preference for removal of the more hindered leaving group was encountered in the acetoxy case described above. When compared with this result, obtained under the TFA conditions, use of triphenylcarbenium tetrafluoroborate to convert **3d** to the corresponding dienyl cations again favoured the removal of the less hindered ether, but did not improve on the selectivity for the 1-methyldienyl system obtained with the methyl ether **3b**, producing only a 1 : 1 mixture of cationic dienyl complexes.

Optical purity of products

In a series of chemical correlations and NMR experiments the optical purity of the 6-*endo*-methoxy-1-methylcyclohexadienyl complex **4b** was determined. Alkylation of the mixture of **4b** and **5b** with the enolate of dimethyl malonate produced the expected mixture of complexes **8** and **9** which proved easy to separate by chromatography. The 1-methyl isomer **8** was examined in the presence of the chiral shift reagent tris[3-(trifluoromethylhydroxymethylene)-*d*-camphorato]europium(III) (**11**), a method we have previously demonstrated [14] as a general procedure for measurement of optical purity of malonate adducts obtained from a variety of dienyl cations. In the case of **8**, only signals due to one diastereoisomer could be detected. Since **8** is available only from biologically derived **2a**, examination of racemic **8** to confirm the applicability of our NMR method in this new series of 6-methoxy-substituted complexes could not be attempted. Instead, the additional OMe group was removed in a sequence of steps to prepare a simplified substrate for further NMR examination. Reduction of the mixture of **4b** and **5b** with sodium borohydride afforded a mixture of products from which the 6-methoxy-1-methyl isomer **12**, formed by reduction of **4b**, was obtained in 38% yield. Treatment of **12** with TFA produced the known [15] dienyl complex **13** which was precipitated by addition of ammonium hexafluorophosphate. This 2-methyl cation had already been shown [14]



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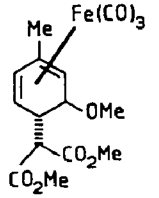

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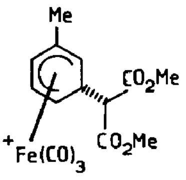

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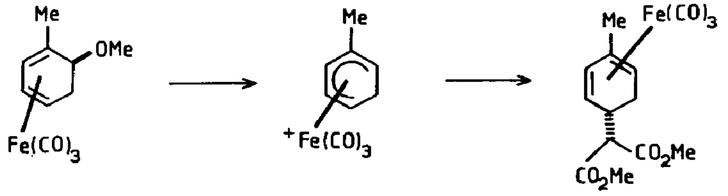

12 13 14

to be suitable for NMR analysis of optical purity. Alkylation with dimethyl malonate, performed as described [14] for the racemic sample, afforded the adduct **14**. Examination of the NMR spectrum of **14** in the presence of **11** again showed only a single pair of methoxy signals arising from the two diastereotopic ester groups. This result indicated that the salt **4b** was enantiomerically pure, a finding confirmed by the addition of a small quantity of racemic **14** to the NMR experiment. Two further ester signals arising from the minor enantiomer of **14** were then visible as expected for a mixture of diastereoisomeric adducts with the chiral shift reagent. In addition to these signals, a trace of a further complex was also apparent in the both NMR spectra. Since this material was not the minor enantiomer of **14**, it seems probable that it arose from a product derived from a trace of a regioisomer of **12** that had remained through an imperfect separation of the reduction products obtained from **4b** and **5b**.

Since the absolute configurations of (+)**2a** [16] and (+)**13** [17] are both known, the preparation of (+)**3b** from the diol **2a**, and its conversion to **13**, confirmed the absolute configurations of the organometallic portions of the complexes employed as intermediates in these reaction sequences. The results require the *endo* stereochemistry assigned above to the diene complexes **3a**–**3d**, and hence substantiate the 6-*endo* formulation of the dienyl complexes obtained from them.

Second demethoxylation

The alkylation product **8** can be converted into the dienyl complex **10** by a second demethoxylation. Reaction with TFA produced **10**, which was precipitated in 84% yield by addition of ammonium hexafluorophosphate.

Conclusion

The use of *cis*-diol substitution on cyclohexadiene rings both to control diastereoface selectivity in complexation reactions and to facilitate activation for double alkylation sequences, has been established as a practical method to provide access to homochiral dienyl complexes with correct functionality to serve as synthetic equivalents of stereocontrolled cyclohexadiene dication synthons of type **1**, X = Me. In view of the variety of *cis* diols available from microbial oxidation of substituted arenes [18], these procedures are suited to further development for general use. The preparation of cationic cyclohexadienyl complexes bearing 6-*exo* alkyl substituents by the elaboration of diol complexes has been demonstrated both in this study and in our examination of cyclohexadiene-5,6-diol itself [4]. Although iron [13,19] and molybdenum [20] complexes of this type have been previously prepared by others, this paper describes the first access to complexes of this type in homochiral form.

The unsymmetrical substitution pattern on the organic ligand, inevitable in such complexes, make regiocontrol of central importance in the development of efficient reaction sequences. By formation of diol derivatives with suitable ether or ester groups, and by selection of suitable electrophilic reagents, we have been able to manipulate the ratio of regioisomers formed to favour either the 1-methyl isomer (5 : 1) or the 2-isomer (3 : 2) in the product. Future development by further examination of these control strategies, which appear either to extract the most easily accessible group or to force out the most severely crowded group, will aim to improve both the selectivity and the understanding of the salt formation process in cyclohexadiene-5,6-diol derivatives.

Experimental

Infrared spectra were recorded on a Perkin–Elmer 257 grating infrared spectrometer with 10 × scale expansion for measurements in the metal carbonyl region. ^{1}H NMR data were recorded on a Jeol JNM-GX400 FT NMR spectrometer and Jeol PMX-60 NMR spectrometer. ^{13}C NMR were recorded on the Jeol JNM-GX400 FT NMR spectrometer (100 MHz). Mass spectra were obtained from a Kratos MS25 mass spectrometer. Chiroptical data were obtained with a Jasco DIP/360 polarimeter and Jasco J-600 circular dichroism instrument (located at the AFRC Institute of Food Research, Norwich).

Diethyl ether and tetrahydrofuran were distilled from benzophenone and sodium. "Petrol" was redistilled 40–60 petroleum ether. (+)-5,6-Dihydroxy-1-methylcyclohexa-1,3-diene (**2a**) ($[\alpha]_D$ +73.4°, *c* 1, cyclohexane) was provided by ICI Biological Products.

Complexation, salt formations, and nucleophile additions were performed under nitrogen.

Preparation of cis-diol derivatives

*5,6-Dimethoxy-1-methylcyclohexa-1,3-diene (**2b**) [20].* Iodomethane (4 ml, 63 mmol) was added to a solution of (+)-5,6-dihydroxy-1-methylcyclohexa-1,3-diene (**2a**) (2 g, 15.9 mmol) in DMSO (10 ml) over ground potassium hydroxide at 0 °C. After $1\frac{1}{2}$ h reaction was quenched with distilled water (50 ml) and the products extracted with dichloromethane (3 × 25 ml). The combined organic layers were washed with distilled water (3 × 25 ml) and dried with brine (50 ml) and magnesium sulphate. Removal of solvent afforded the product as a golden oil (2.08 g; 1.95 g, 12.7 mmol of diene and 0.13 g, 1.1 mmol of 2- and 3-methylanisole), equivalent to an 80% yield of the desired product. ^{1}H NMR ($CDCl_3$): δ 1.72 (3H, bs, 1-Me), 3.92 (2H, m, 5,6-H), 3.40 (6H, s, 5,6-H), 5.84 (3H, m, 2, 3, 4-H). *M/z* 153.0905 ($M^+ - H$, 53%).

*5,6-Diacetoxy-1-methylcyclohexa-1,3-diene (**2c**).* A solution of 5,6-dihydroxy-1-methylcyclohexa-1,3-diene (1.5 g, 11.9 mmol) in pyridine (10 ml) was stirred overnight at 12 °C with acetic anhydride (2.5 ml, 26.2 mmol). Removal of the excess of pyridine and extraction of the residue with diethyl ether (3 × 25 ml), followed by washing (3 × 25 ml, water) and drying (saturated brine (50 ml) and magnesium sulphate) afforded 5,6-diacetoxy-1-methylcyclohexa-1,3-diene (1.08 g, 5.1 mmol) in 43% yield. ^{1}H NMR ($CDCl_3$): δ 1.84 (3H, s, 1-Me), 2.04 (3H, s, OAc), 2.08 (3H, s, OAc), 5.52 (2H, m, 5,6-H), 5.90 (3H, m, 2,3,4-H).

*5,6-Diethoxy-1-methylcyclohexa-1,3-diene (**2d**).* Treatment of a solution of (+)-5,6-dihydroxy-1-methylcyclohexa-1,3-diene (1.5 g, 11.9 mmol) in DMSO (10 ml), over potassium hydroxide (5.6 g, 100 mmol), with iodomethane (3.4 ml, 42.5 mmol), as described by Johnson and Rose [20] for $\frac{1}{2}$ h afforded, after $\frac{1}{2}$ h, the product **2d** (1.26 g, 6.9 mmol) in 58% yield. ^{1}H NMR ($CDCl_3$) δ 1.16 (3H, t *J* 6.7 Hz, CH_3–CH_2O), 1.20 (3H, t *J* 6.7 Hz, CH_3–CH_2O), 1.90 (3H, bs, 1-Me), 3.40–4.20 (6H, m, 5,6-H and 2 × OCH_2), 5.82 (3H, m, 2,3,4-H). *M/z* 182 (M^+, 32%, 182.1305). Aromatic by-products were also obtained.

Complexation of cis-diol derivatives

(+)-(1S)-Tricarbonyl(η^4-5(R), 6(S)-dihydroxy-1-methylcyclohexa-1,3-diene)iron(0) (3a).

Diol (0.5 g, 4 mmol) was added to a solution of diiron nonacarbonyl (4.5 g, 12.4 mmol) in dry THF (40 ml) and the mixture was stirred under nitrogen at room temperature for 18 h. Standard work-up was followed by column chromatography on silica, the iron pentacarbonyl and triiron dodecacarbonyl being eluted with dichloromethane. Treatment of the product with ether afforded gave a yellow crystalline solid (0.42 g, 1.6 mmol) in 35% yield. M.p. 100.1–101.0 °C. $[\alpha]_D$ +72.0° (*c* 0.5, $CHCl_3$); IR ($CHCl_3$): 2049, 1983 cm^{-1}; ^1H NMR ($CDCl_3$): δ 1.64 (3H, s, 1-Me), 3.20–2.60 (3H, m, 4-H, 5-H, 6-H), 3.70 (1H, m, OH), 3.90 (1H, m, OH) 5.08 (1H, d, *J* 2.4 Hz, 3-H), 5.20 (1H, bs, 2-H). *M/z* 238 ($M^+ - CO$), 210, 192. Anal. Found: C, 45.1; H, 3.7. $C_{10}H_{10}FeO_5$ calcd: C, 45.2; H, 3.8%.

(+)-(1S)-Tricarbonyl(η^4-5(R),6(S)-dimethoxy-1-methylcyclohexa-1,3-diene)iron(0) (3b). A solution of 5,6-dimethoxy-1-methylcyclohexa-1,3-diene (1.5 g, 9.6 mmol) in ether (40 ml) was refluxed for 18 h with diiron nonacarbonyl (6.0 g, 16.5 mmol). Filtration through kieselguhr and removal of the excess of solvent and iron pentacarbonyl yielded the product as a mixture with triiron dodecacarbonyl. The pure product was obtained by column chromatography (silica). The iron carbonyl was eluted with petrol and the complex **3b** treated with 5% ether/95% petroleum ether. Removal of the excess of solvent afforded **3b** as a yellow, crystalline solid (1.5 g, 5.1 mmol) in 55% yield. M.p. 49.1–49.6 °C. $[\alpha]_D$ +142.9° (*c* 1, C_6H_{12}); IR (C_6H_{12}): 2059, 1997, 1970 cm^{-1}; ^1H NMR (C_6D_6): δ 1.43 (3H, s, 1-Me), 2.67 (1H, dt *J* 6.1, 1Hz, 6-H), 2.71 (1H, dq *J* 6.6, 2.4, 2.4 Hz, 4-H), 2.95 (1H, qd *J* 6.1, 2.4, 0.7 Hz, 5-H), 3.04 (3H, s, 6-OMe), 4.41 (1H, qd *J* 6.6, 4.3, 0.7 Hz, 3-H), 4.44 (1H, m, 2-H). *M/z* 294 (molecular ion), 266, 238. CD (C_6H_{12}) $\Delta\epsilon$ (−0.38 (357 nm), +5.80 (300 nm). Anal. Found: C, 48.9; H, 4.8. $C_{12}H_{14}FeO_5$ calcd.: C, 49.0; H, 4.8%.

(+)-(1S)-Tricarbonyl(η^4-5(R),6(S)-diacetoxy-1-methylcyclohexa-1,3-diene)iron(0) (3c). A solution of 5,6-diacetoxy-1-methylcyclohexa-1,3-diene (1 g, 4.76 mmol) in toluene (30 ml) was sonolysed for 22 h with diiron nonacarbonyl (6.7 g, 19.0 mmol). The mixture was filtered through kieselguhr and the excess of toluene removed under reduced pressure. Chromatography (silica, petroleum ether) removed triiron dodecacarbonyl. Elution with ethyl acetate afforded tricarbonyl(η^4-5,6-diacetoxy-1-methylcyclohexa-1,3-diene)iron(0) (0.16 g, 0.45 mmol) as a yellow crystalline solid in 9.6% yield. M.p. 142.1–143.0 °C. $[\alpha]_D$ +94.4° (*c* 0.5, $CHCl_3$); IR (C_6H_{12}): 2059, 1998, 1982 cm^{-1}; ^1H NMR ($CDCl_3$): δ 1.52 (3H, s, 1-Me), 2.08 (3H, s, OAc), 2.12 (3H, s, OAc), 2.92 (1H, bs, 4-H), 4.88 (2H, m, 5, 6-H), 5.22 (2H, m, 2, 3-H). CD ($CHCl_3$) $\Delta\epsilon$ −0.53 (352 nm), +6.69 (298). Anal. Found: C, 48.1; H, 4.0. $C_{14}H_{14}FeO_7$ calcd.: C, 48.0; H, 4.0%.

(+)-(1S)-Tricarbonyl(η^4-5(R),6(S)-diethoxy-11-methylcyclohexa-1,3-diene)iron(0) (3d). A solution of 5,6-diethoxy-1-methylcyclohexa-1,3-diene (0.5 g, 2.7 mmol) in ether (40 ml) was refluxed for 19 h with diiron nonacarbonyl (3 g, 8.26 mmol). The mixture was filtered through kieselguhr and concentrated under reduced pressure. Chromatography (silica, petrol) of the residue removed triiron dodecacarbonyl. Treatment with 5% ether/95% petrol afforded tricarbonyl(η^4-5,6-diethoxy-1-methylcyclohexa-1,3-diene)iron(0) (0.22 g, 0.7 mmol) in 25% yield. $[\alpha]_D$ +129.6 (*c* 0.5, C_6H_{12}); IR (C_6H_{12}): 2058, 1997, 1970 cm^{-1}; ^1H NMR ($CDCl_3$): δ 1.12 (3H, t *J* 6.7 Hz, CH_3-CH_2O), 1.16 (3H, t, *J* 6.7 Hz, CH_3-CH_2O), 2.80–3.80 (7H, m, 2 ×

OCH_2), 4-, 5-, 6-H), 5.02 (1H, bs, 3-H), 5.03 (1H, m, 3-H). CD (C_6H_{12}) $\Delta\epsilon$ −0.44 (357 nm), 5.90 (302 nm). M/z 294 ($M^+ - CO$), 266 ($M^+ - 2CO$, 42%) [294.0562, CI(NH_3) 323.0589 ($M^+ + H$)].

Formation of cationic η^5-dienyl complexes with TFA (Method A)

A solution of tricarbonyl(η^4-5,6-dimethoxy-1-methylcyclohexa-1,3-diene)iron(0) (1.64 g, 5.6 mmol) in TFA (3.28 ml) was stirred at 0 °C for 1 h. The salt was precipitated by addition of aqueous ammonium hexafluorophosphate (3.28 ml, 5 g/10 ml solution) at −78 °C, followed by warming to room temperature. The precipitate was collected by vacuum filtration the excess of ammonium hexafluorophosphate was removed with distilled water (4 × 5 ml portions), and the residue was air dried overnight.

The products (1.71 g, 4.2 mmol) were obtained, in 1 : 1 ratio, as a microcrystalline yellow powder in 74% yield. An analytically pure sample was prepared by reprecipitation from acetonitrile.

Formation of cationic η^5-dienyl complexes with triphenylcarbenium tetrafluoroborate (Method B)

A solution of triphenylcarbenium tetrafluoroborate (0.25 g, 0.74 mmol) in dry dichloromethane (1 ml) was added to a stirred solution of complex (0.2 g, 0.68 mmol) in dry dichloromethane (3 ml). After $\frac{1}{2}$ h stirring under nitrogen, the product (0.19 g, 0.54 mmol) was precipitated, by addition of wet ether (12 ml), in 78% yield.

Treatment of the complex on a larger scale (1.6 g, 5.4 mmol) with triphenylcarbenium tetrafluoroborate (2 g, 6 mmol) afforded the product of hydride abstraction (the 1-methyl-5,6-dimethoxy salt) (1.1 g, 2.6 mmol) in 48% yield. The demethoxylation products were also found to be present (2.1 mmol) in lower yield (33%).

Formation of cationic η^5-dienyl complexes with HBF_4 in acetic anhydride (Method C)

Tetrafluoroboric acid etherate (0.5 ml of a 52% solution) was added to a stirred solution of the neutral complex **3a** (0.25 g, 0.9 mmol) in acetic anhydride at −15 °C under nitrogen. After 1 h, ether (10 ml) was added and the products separated out. Collection and drying of the precipitate afforded the products (0.23 g, 0.6 mmol) in 62% overall yield.

Formation of cationic η^5-dienyl complexes with triphenylcarbenium hexafluorophosphate in acetic anhydride (Method D)

A solution of triphenylcarbenium hexafluorophosphate (0.4 g, 1.03 mmol) in acetic anhydride (6 ml) was added, at room temperature, to a solution of tricarbonyl(η^4 5,6-dihydroxy-1-methylcyclohexa-1,3-diene)iron(0) (0.25 g, 0.93 mmol) in acetic anhydride (2 ml). The mixture was stirred for $\frac{1}{2}$ h under nitrogen before being poured into moist ether to give a mixture of tricarbonyl(η^5-6-acetoxy-1-methylcyclohexadienyl)iron(+1) and tricarbonyl(η^5-6-acetoxy-2-methylcyclohexadienyl) iron(+1) as a yellow precipitate (0.23 g 0.53 mmol) in 56% yield.

*The following mixtures were prepared by the methods: (+)-(1S)-Tricarbonyl(η^5-6(S)-methoxy-1-methylcyclohexa-1,3-dienyl)iron(1+) hexafluorophosphate(1−) (**4b**) and*

*(2S)-tricarbonyl(η^5-6(S)-methoxy-2-methylcyclohexa-1,3-dienyl)iron(1 +) hexafluorophosphate(1 −) (**5b**) (Methods A and B)*

*(+)-(1S)-Tricarbonyl(η^4-6(S)-methoxy-1-methylcyclohexa-1,3-dienyl)iron(1 +) hexafluorophosphate(1 −) (**4b**).* $[\alpha]_D$ +37.8° (*c* 1, CH_3CN). IR (CH_3CN)CN): 2116, 2067 cm^{-1}; ^{1}H NMR (CD_3CN) δ 1.70 (3H, s, 1-Me), 3.49 (3H, s, 6-OMe), 3.87 (1H, s, 6-H), 4.02 (1H, d *J* 7.6 Hz, 5-H), 5.56 (1H, d *J* 5.2 Hz, 2-H), 5.82 (1H, dd *J* 5.5, 7.6 Hz, 4-H), 6.86 (1H, dd, *J* 5.5, 5.2 Hz, 3-H). Anal. Found: C, 32.5; H, 2.6. $C_{11}H_{11}F_6FeO_5P$ calcd.: C, 32.4; H, 2.7%.

*(2S)-Tricarbonyl(η^4-6(S)-methoxy-2-methylcyclohexa-1,3-dienyl)iron(+ 1) hexafluorophosphate(1 −) (**5b**).* IR (CH_3CN): 2116, 2067 cm^{-1}; ^{1}H NMR (CD_3CN): δ 2.12 (3H, s, 2-Me), 3.44 (3H, s, 6-OMe), 3.81 (1H, s, 6-H), 3.94 (1H, s, 1-H), 4.05 (1H, d *J* 7.6 Hz, 5-H), 5.81 (1H, m, 4-H), 6.88 (1H, m, 3-H). Anal. Found: C, 32.5; H, 2.6. $C_{11}H_{11}F_6FeO_5P$ calcd.: C, 32.4; H, 2.7%.

*(1S)-Tricarbonyl(η^4-6(S)-acetoxy-1-methylcyclohexa-1,3-dienyl)iron(1 +) hexafluorophosphate(1 −) (**4c**) and (2S)-tricarbonyl(η^5-6(S)-acetoxy-2-methylcyclohexa-1,3-dienyl)-iron(1 +) hexafluorophosphate(1 −) (**5c**) Methods B, C and D)*

*(1S)-Tricarbonyl(η^5-6(S)-acetoxy-1-methylcyclohexa-1,3-dienyl)iron(+ l) hexafluorophosphate(1 −) (**4c**).* IR (CH_3CN): 2117, 2071 cm^{-1}; ^{1}H NMR (CD_3CN): δ 1.68 (3H, s, 1-Me), 2.19 (3H,s, 6-OAc), 4.05 (1H, d *J* 7.2 Hz, 5-H), 5.07 (1H, s, 6-H), 5.68 (1H, m, 2-H), 5.89 (1H, m, 5-H) 6.95 (1H, m, 3-H). Anal. Found: C, 32.74; H, 2.4. $C_{12}H_{11}F_6FeO_5P$ calcd.: C, 33.05; H, 2.5%.

*(2S)-Tricarbonyl(η^5-6(S)-ethoxy-2-methylcyclohexa-1,3-dienyl)iron(+ 1) hexafluorophosphate(1 −) (**5c**).* IR (CH_3CN): 2114, 2068 cm^{-1}; ^{1}H NMR (CD_3CN): δ 1.26 (3H, t *J* 6.7 Hz, CH_3–CH_2O), 2.11 (3H, s, 2-Me), 3.58 (2H, m, OCH_2), 3.80–4.10 (3H, m, 1-, 5-, 6-H) 5.78 (1H, m, 4-H) 6.87 (1H, bs, 3-H). Anal. Found C, 34.1; H, 2.9. $C_{12}H_{13}F_6FeO_4P$ calcd.: C, 34.1; H, 3.1%.

*(1S)-Tricarbonyl(η^5-6(S)-ethoxy-1-methylcyclohexa-1,3-dienyl)iron(1 +) hexafluorophosphate(1 −)**4d**) and (2S)-tricarbonyl(η^5-6(S)-ethoxy-1-methylcyclohexa-1,3-dienyl)-iron(1 +) hexafluorophosphate(1 −) (**5d**) (Methods A and B)*

*(1S)-Tricarbonyl(η^5-6(S)-ethoxy-1-methylcyclohexa-1,3-dienyl)-iron(1 +) hexafluorophosphate(1 −) (**4d**).* IR (CH_3CN): 2114, 2068 cm^{-1}; ^{1}H NMR (CD_3CN): δ 1.25 (3H, t *J* 6.7 Hz, CH_3–CH_2O), 1.70 (3H, bs, 1-Me), 3.58 (2H, m, OCH_2), 3.80–4.10 (2H, m, 5-, 6-H), 5.57 (1H, d, *J* 4.6 Hz, 2-H), 5.78 (1H, m, 4-H), 6.87 (1H, bs, 3-H). Anal. Found: C, 34.1; H, 2.9. $C_{12}H_{13}F_6FeO_4P$ calcd.: C, 34.1; H, 3.1%.

*(2S)-Tricarbonyl(η^5-6(S)-ethoxy-2-methylcyclohexa-1,3-dienyl)iron(1 −) hexafluorophosphate(1 −) (**5d**).* IR (CH_3CN): 2114, 2068 cm^{-1}; ^{1}H NMR (CD_3CN): 1.26 (3H, t *J* 6.7 Hz, CH_3–CH_2O), 2.11 (3H, s, 2-Me), 3.58 (2H, m, OCH_2), 3.80–4.10 (3H, m, 1-, 5-, 6-H) 5.78 (1H, m 4-H), 6.87 (1H, bs, 3-H) Anal. Found: C, 34.1; H, 2.9. $C_{12}H_{13}F_6FeO_4P$ calcd.: C, 34.1; H, 3.1%.

*(+)-(5S)-Tricarbonyl(η^4-(S)-methoxy-5-methylcyclohexa-2,4-dienone)iron(0) (**6**)*

The hydride abstraction was performed on a 5.4 mmol scale as described above. The product was precipitated with ether and dissolved in water (10 ml). The solution of salts (1.05 g; 0.65 g, 1.7 mmol of the 5-methoxy cation) in water (10 ml) was heated for 1 h (steam bath). The largely insoluble dienone was extracted with ether (3 × 10 ml) and the combined extracts were washed with water (3 × 10 ml), then with brine (30 ml), and then dried over magnesium sulphate. Removal of solvent afforded the dienone complex (0.26 g, 0.9 mmol) as a yellow crystalline solid in 54% yield. M.p. 99.0–100.4° C. $[\alpha]_D$ +546.4, (*c* 0.5, C_6H_{12}); IR (C_6H_{12}): 2051, 1995, 1961 and 1670 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ 1.60 (3H, bs, 4-Me), 3.12 (1H, m, 4-H) 3.30 (1H, bs, 6-H) 3.66 (3H, s, 6-OMe), 5.30 (1H, m, 2-H) 5.62 (1H, m, 3-H). *M/z* 278 (M^+), 250, 222. Anal. Found: C, 47.5; H, 3.5. $C_{11}H_{10}FeO_4$ calcd.: C, 47.5; H, 3.6%.

*Purification of the dienyl complex **4b** by deprotonation / reprotonation*

Triethylamine (0.1 ml, 0.72 mmol) was added to a stirred solution of 1- and 2-methyl salts, **4b** and **5b**, (equivalent to 0.097 g, 0.24 mmol) in acetone (2 ml) at 0° C under nitrogen. After $\frac{1}{2}$ h the mixture was poured into ether and filtered. The filtrate was concentrated by rotary evaporation and transferred to a silica column. Elution with ether followed by removal of the excess of solvent afforded the triene as a yellow oil. The triene was protonated with TFA by the standard procedure to afford *(+)-(1S)-tricarbonyl(η^4-6(S)-methoxy-1-methylcyclohexa-1,3-dienyl)iron(1 +) hexafluorophosphate(1 −)* (***4b***) (approximately 97% pure) (0.045 g, 0.11 mmol) in 46% recovery.

*(−)-(5S)-Tricarbonyl[dimethyl(η^4-6(S)-methoxy-5-methylcyclohexa-2,4-dien-1(S)-yl) propanedioate]iron(0) (**8**) and (4S)-tricarbonyl[dimethyl(η^4-6(S)-methoxy-4-methylcyclohexa-2,4-dien-1(S)-yl)propanedioate]iron(0) (**9**)*

A stock solution of dimethylsodiomalonate (5.4 mmol) in dry THF (20 ml) was prepared by the action of sodium hydride (5.6 mmol) on dimethylmalonate (5.4 mmol). An aliquot of the stock solution (10 ml, 2.70 mmol) was added by standard syringe techniques to a stirred suspension of salt (33 : 29 1- and 2-methyl salts, 1 g, 2.45 mmol) in dry THF (10 ml) under nitrogen at 0° C. After the dissolution of the salt and the disappearance of the associated IR bands, the mixture was poured into brine (50 ml) and extracted with ether (3 × 25 ml). Washing with water (3 × 25 ml), drying and removal of the excess of solvent afforded the products as a yellow oil (0.59, 1.5 mmol) in 61% yield. Column chromatography (silica, 10% ether/petrol) separated the two isomers in 1/1 ratio. The 1-methyl complex crystallized at low temperature (*c.* −20° C) and an analytically pure sample was obtained by recrystallisation from petrol.

*(−)-(5S)-Tricarbonyl[dimethyl(η^4-6(S)-methoxy-5-methylcyclohexa-2,4-dien-1(S)-yl)-propanedioate]iron(0) (**8**).* M.p. 64.6–66.3° C. $[\alpha]_D$ −47.1° (*c* 1, C_6H_{12}); IR (C_6H_{12}): 2055, 1994, 1974 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ 1.56 (3H, s, 5-Me), 2.57 (1H, m, 1-H), 2.91 (1H, m, 6-H), 3.09 (1H, bs, 2-H), 3.21 (1H, *J* 7.3 Hz, $HC(CO_2Me)_2$), 3.32 (3H, S, 6-OMe), 3.72 (3H, s, OMe propanedioate), 3.73 (3H, S, OMe propanedioate), 5.13 (2H, m, 2, 3-H). *M/z* 366 (M^+ − CO), 338, 310. Anal. Found: C, 48.9; H, 4.7. $C_{16}H_{18}FeO_8$ calcd.: C, 48.8; H, 4.6%.

*(4S)-Tricarbonyl[dimethyl(η^4-6(S)-methoxy-4-methylcyclohexa-2,4-diene-1(S)-yl)propanedioate)iron(0) (**9**).* IR (C_6H_{12}): 2056, 1994, 1975 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ 2.12 (3H, bs, 4-Me), 2.40–3.10 (4H,m, 1-H, 2-H, 5-H, 6-H), 3.32 (3H, S, 6-OMe), 3.70 (3H, s, OMe propanedioate), 3.72 (3H, s, OMe propanedioate), 5.20 (1H, m, 3-H). *M/z* 394 (M^+) 394, 366, 338, 310. Anal. Found: C, 48.1; H 4.6. $C_{16}H_{18}FeO_8$ calcd.: C, 48.8; H, 4.6%.

Reduction of (+)-(1S)-Tricarbonyl(η^5-6(S)-methoxy-1-methylcyclohexa-1,3-dienyl)iron(1+) hexafluorophosphate(1−) ***(4b)*** *and (2S)-tricarbonyl(η^5-6(S)-methoxy-2-methylcyclohexa-1,3-dienyl)iron(1+) hexafluorophosphate(1−)* ***(5b)***

Sodium borohydride (7.4 mg, 1.9 mmol) was added to a stirred solution of salt (0.71 g, 1.7 mmol), in dry acetonitrile (7 ml), under nitrogen. After $\frac{3}{4}$ h the reaction was quenched with water (50 ml) and the products extracted with ether (3 × 25 ml). The combined organic phases were washed with water (3 × 25 ml) then with brine (25 ml), and dried over magnesium sulphate. Removal of the excess of solvent yielded the products as a yellow oil (0.28 g, 1.1 mmol) in 62% yield. Separation was effected by column chromatography (silica, petrol) which afforded *(1S)-tricarbonyl(η^4-6(S)-methoxy-1-methylcyclohex-1,3-diene)iron(0)* (***12***) in 38 % yield. ^{1}H NMR ($CDCl_3$): δ 1.4–2.0 (2H, m, 5-*endo, exo*-H), 1.60 (3H, bs, 1-Me), 3.00 (1H, m, 4-H), 3.20 (4H, bs, 6-H, 6-OMe), 5.04 (2H, m, 2-, 3-H).

The other reduction products were discarded.

(+)-(2S)-Tricarbonyl(η^5-2-methylcyclohexa-1,3-dienyl)iron(1+) hexafluorophosphate(1−) ***(13)***. A solution of the 6-monomethoxy-1-methyl complex (0.17 g, 0.6 mmol) in TFA (0.35 ml) afforded, on precipitation with ammonium hexafluorophosphate (0.18 g, 1.1 mmol), the product (0.13 g, 0.3 mmol) in 52% yield. $[\alpha]_D$ +25.1° (*c* 1, CH_3CN) (literature value for partially resolved material: $[\alpha]_D$ +0.6° (*c* 3 CH_3CN) [16]). IR (CH_3CN): 2112, 2063 cm^{-1}; ^{1}H NMR (CD_3CN): δ 1.90 (1H, d obscured by solvent signal, 6-H), 2.14 (3H, s, 2-Me), 2.95 (1H, dt *J* 15.6, 6.1 Hz), 4.05 (1H, d *J* 6.1 Hz, 1-H), 4.25 (1H, m, 5-H), 5.79 (1H, dd, *J* 6.4, 5.5 Hz, 1-H), 7.01 (1H, d *J* 5.5 Hz, 3-H).

(−)-(4S)-Tricarbonyl[dimethyl(η^5-4-methylcyclohexa-2,4-dien-1(R)-yl)propanedioate]iron(0) ***(14)***. Reaction of the salt **13** (0.12 g, 0.3 mmol) with dimethylsodiomalonate (0.34 mmol) in the usual manner afforded a yellow oil (0.08 g, 0.22 mmol) ($[\alpha]_D$ −2.4, *c* 1, C_6H_{12}) which was identified as the title product **14** (72%) by comparison of its ^{1}H NMR data with those available for the racemic compound [13].

(+)-(3S)-Tricarbonyl[dimethyl(η^5-3-methylcyclohexa-2,4-dien-1(R)-yl)propanedioate]iron(1+) hexafluorophosphate(1−) ***(10)***. A solution of the 5-malonyl-6-methoxy complex (0.06 g, 0.15 mmol) in TFA afforded in the usual manner a yellow microcrystalline solid (0.07 g, 0.13 mmol) in 87% yield. $[\alpha]_D$ +11.5° (*c* 1, CH_3CN). IR (CH_3CN): 2118, 2070 cm^{-1}; ^{1}H NMR (CD_3CN): δ 2.13 (3H, s, 2-Me), 2.86 (1H, d *J* 8.9, $HC(CO_2Me)_2$), 3.55 (1H, m, 6-H), 3.66 (3H, s, OMe propanedioate), 3.67 (3H, s, OMe propanedioate), 4.24 (1H, d *J* 5.8 Hz, 1-H), 4.44 (1H, dd *J* 6.1, 7.0 Hz, 5-H), 5.87 (1H, dd *J* 5.5, 7.0 Hz, 4-H), 6.87 (1H, d, *J* 5.5 Hz, 3-H). Anal. Found: C, 34.8; H 2.8. $C_{15}H_{12}F_6FeO_7P$ calcd.: C, 35.5; H, 3.0%.

Acknowledgements

GRS thanks The Royal Society for a 1983 University Research Fellowship. PWH thanks the SERC and ICI Biological Products for a CASE studentship.

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