Chiral Organometallic NADH Mimics: Preparation and X-Ray Crystal Structure of Racemic (*RS*)-[Fe(η^5-C_5H_5)(CO)(PPh_3)(1-methyl-1,4-dihydronicotinoyl)] and Homochiral(*R*)-(−)-[Fe(η^5-C_5H_5)(CO){PPh_2(O-[(−)-menthyl†])}(1-methyl-1,4-dihydronicotinoyl)] and Asymmetric Reduction of Ethyl Benzoylformate

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The racemic complex (*RS*)-[Fe(η^5-C_5H_5)(CO)(PPh_3)(1-methyl-1,4-dihydronicotinoyl)] has been prepared and shown to function as a NADH mimic. An X-ray crystal structure revealed that one face of the 1,4-dihydronicotinoyl moiety is essentially blocked by the triphenylphosphine ligand. The homochiral complex (*R*)-(−)-[Fe(η^5-C_5H_5)(CO)(PPh_2(O-[(−)-menthyl])](1-methyl-1,4-dihydronicotinoyl)] possessing the sterically demanding chiral auxiliary [Fe(η^5-C_5H_5)(CO){PPh_2(O)-(−)-menthyl)}] at C-3 has also been prepared and shown to reduce ethyl benzoylformate to ethyl mandelate in 52% enantiomeric excess by a combination of steric and chelation control.

During the past decade there has been considerable interest in creating model compounds mimicing the activity of the coenzyme NADH.[1,2] In a biological system the coenzyme reacts directly with substrates in an environment constructed by the apoenzyme resulting in high stereospecificity and catalytic rate. However, in biomimetic systems it is essential that a metal ion (*e.g.* Mg^{2+}) is employed in order to facilitate reaction and exert stereocontrol during the hydride transfer step to a prochiral substrate such as a reactive ketone. Generally, model 1,4-dihydropyridine compounds possess a polar functionality at C-3, which, by chelation of the magnesium ion to both the polar function and the substrate, delivers and orientates the substrate over the reaction site. In the majority of early models, the 1,4-dihydropyridines possessed a chiral N-substituted amide[1] at C-3 although recent models have imparted a high degree of chirality transfer by utilising a sulphinyl[3] or hydroxymethyl[4] moiety at this position. In order to achieve high stereocontrol during the hydride transfer step it is essential that only one of the prochiral hydrogens at C-4 is available for reaction and that the orientation of the substrate is well defined.[1] In the models developed by Ohno[2] and others[4,5] it was possible to ensure that the mode of hydride transfer was stereoselective by incorporating a stereogenic centre at C-4, thus obviating the need for discrimination at C-4, as well as maintaining a polar functional group at C-3. It was our opinion that a similar stereoselectivity could be achieved by the utilisation of a sterically demanding chiral auxiliary at C-3 thereby preventing access of the substrate to one of the prochiral hydrogens. Since the chiral iron auxiliary [Fe(η^5-C_5H_5)(CO)(PPh_3)] attached to a variety of organic ligands has been shown to exert high stereocontrol in a wide variety of reactions[6] it was of interest to incorporate this auxiliary at C-3 of a 1,4-dihydronicotinoyl moiety.

The initial objective of this study was the preparation of racemic [Fe(η^5-C_5H_5)(CO)(PPh_3)(1-methyl-1,4-dihydronicotinoyl)] **5** and the assessment of its utility in the reduction of ethyl benzoylformate. The results of this study which are described below, lead to the preparation of homochiral **7**[7] which was also assessed as a NADH mimic.

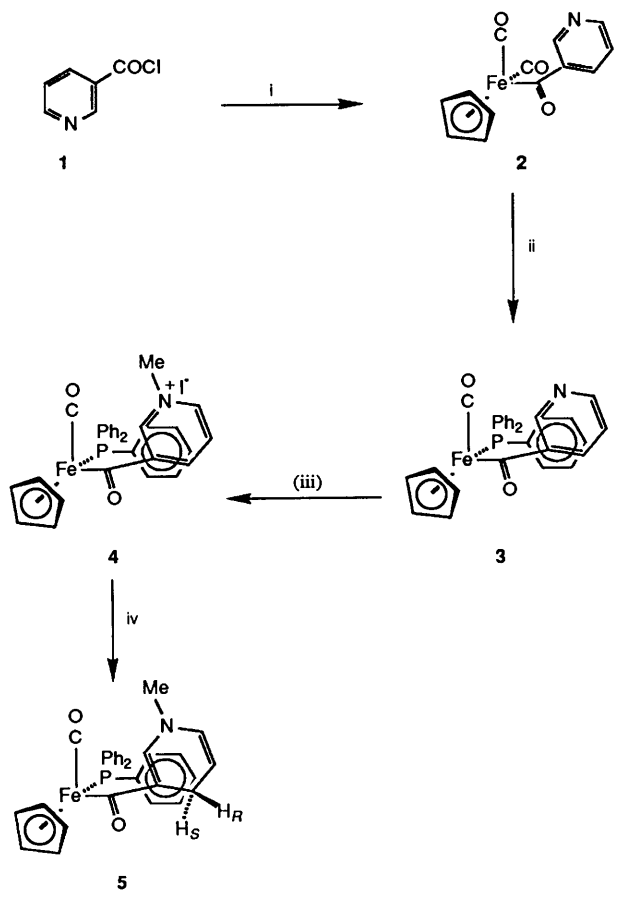
† For clarity only the absolute configuration of the iron centre is given; (−)-menthol is (1*R*,2*S*,5*R*)-(−)-2-isopropyl-5-methylcyclohexan-1-ol. Menthyl is the radical formed by loss of the 1-hydroxy group: in (−)-menthyl the − indicates that solutions of these molecules rotate plane polarised light to the left.

Results and Discussion

The starting material used in the synthesis of complex **5** was cyclopentadienyldicarbonyliron anion, which was readily prepared according to a literature method.[8] Thus, treatment of the anion with a solution of nicotinoyl chloride[9] **1** in tetrahydrofuran at −78 °C, followed by warming to room temperature afforded the nicotinoyliron complex **2** in 72% yield. Ligand exchange of carbon monoxide for triphenylphosphine by photolysis of a solution of **2** in cyclohexane gave (*RS*)-[Fe(η^5-C_5H_5)(CO)(PPh_3)(nicotinoyl)] **3** in 81% yield (Scheme 1), the ^{1}H NMR data of which was consistent with a C-3 substituted nicotinoyl derivative.[10,11] Treatment of complex **3** with iodomethane afforded in quantitative yield the pyridinium salt **4**, which was readily reduced utilising sodium dithionite[2] to afford the corresponding 1,4-dihydronicotinoyl complex **5** in 85% yield (Scheme 1). Other hydride sources were investigated but were either inefficient or gave mixtures of the 1,4- and 1,2-reduction products. The ^{1}H NMR (300 MHz) spectrum of complex **5** indicated the presence of three olefinic protons characteristic of a 1,4-dihydropyridine.[10,11]

An X-ray crystal structure analysis of complex **5** (Fig. 1) shows the conformation adopted in the solid state and reveals the pseudo-octahedral geometry around iron[12] with the nicotinoyl moiety adopting the expected[5] conformation with C-4 *syn* to the nicotinoyl carbonyl oxygen. Final atomic positional co-ordinates are listed in Table 1 and selected bond angles and torsional angles are given in Table 2. Of interest is the O(1)–C(1)–C(2)–C(6) torsional angle of 11° indicating that the carbonyl dipole is orientated *syn* with respect to the *pro-R* hydrogen. This is clearly indicated in the projection shown in Fig. 2 which also reveals that the *pro-S* hydrogen at C-4 is shielded by the triphenylphosphine ligand. Consistent with such a conformation is the significant difference observed in the chemical shifts (δ 2.92 and 2.35) of the two diastereotopic hydrogens at C-4. The relevance of the carbonyl dipole adopting an out-of-plane orientation *syn* to the departing hydride has recently been discussed in terms of the stereoselectivity of hydride transfer.[5]

In order to determine whether the formation of the 1,4-dihydronicotinoyl moiety of complex **5** is stereospecific, the reduction with sodium dithionite was carried out in the presence of deuterium oxide. Upon work-up a mixture of the deuteriated diastereoisomers **6a** and **6b** was obtained as a 4:1 mixture (Scheme 2). Comparison of the ^{1}H and ^{2}H NMR spectra of the mixture with the ^{1}H NMR spectrum of complex



Scheme 1 *Reagents and conditions:* i, $Na[(\eta^5\text{-}C_5H_5)(CO)_2Fe]$, THF, −78 °C (72%); ii, PPh_3, cyclohexane, *hv* (81%); iii, MeI, CH_2Cl_2 (100%); iv, $Na_2S_2O_4$, $NaHCO_3$, H_2O, MeOH, CH_2Cl_2 (85%)

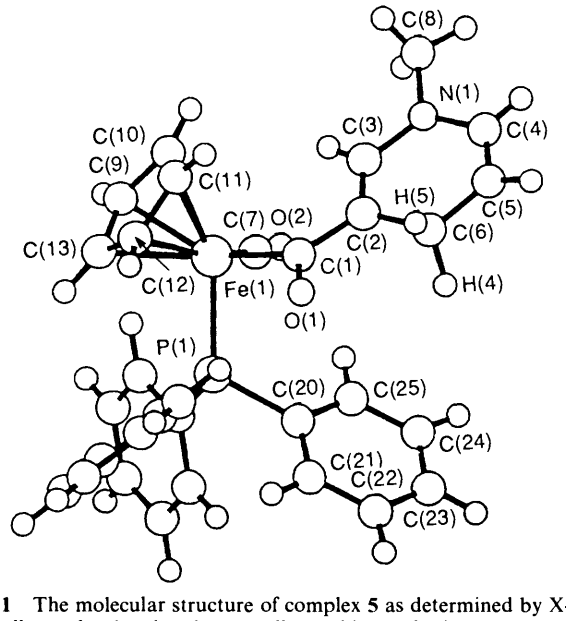


Fig. 1 The molecular structure of complex **5** as determined by X-ray crystallography showing the crystallographic numbering

Table 1 Fractional atomic coordinates for complex **5**

Atom	*x/a*	*y/b*	*z/c*
Fe(1)	0.426 10(9)	−0.055 89(4)	0.715 02(3)
P(1)	0.317 5(2)	−0.144 76(6)	0.769 79(6)
O(1)	0.462 2(5)	−0.185 4(2)	0.645 5(2)
O(2)	0.096 1(5)	0.018 6(2)	0.684 6(2)
N(1)	0.226 6(7)	−0.008 4(3)	0.496 2(2)
C(1)	0.403 9(6)	−0.121 4(3)	0.639 4(2)
C(2)	0.324 3(7)	−0.100 8(3)	0.575 2(2)
C(3)	0.293 3(7)	−0.030 4(3)	0.557 2(2)
C(4)	0.190 9(9)	−0.063 9(4)	0.450 8(3)
C(5)	0.221 1(9)	−0.135 5(4)	0.463 7(3)
C(6)	0.292 8(9)	−0.163 8(3)	0.527 4(3)
C(7)	0.225 4(6)	−0.013 4(3)	0.695 5(2)
C(8)	0.213(1)	0.069 1(4)	0.478 8(3)
C(9)	0.549 4(8)	0.039 0(3)	0.761 5(3)
C(10)	0.584 9(8)	0.036 1(3)	0.698 6(3)
C(11)	0.677 9(7)	−0.031 5(3)	0.692 1(3)
C(12)	0.693 6(7)	−0.070 4(3)	0.748 8(3)
C(13)	0.614 9(7)	−0.026 0(3)	0.793 2(3)
C(14)	0.185 4(6)	−0.111 0(3)	0.829 8(2)
C(15)	0.081 6(8)	−0.160 2(3)	0.857 9(3)
C(16)	−0.016 4(8)	−0.134 8(4)	0.903 7(3)
C(17)	−0.012 3(9)	−0.060 8(4)	0.920 6(3)
C(18)	0.089(1)	−0.011 9(4)	0.893 1(3)
C(19)	0.189 8(8)	−0.037 2(3)	0.847 6(2)
C(20)	0.165 3(6)	−0.212 5(3)	0.727 0(2)
C(21)	0.177 1(7)	−0.288 2(3)	0.737 1(3)
C(22)	0.053 3(8)	−0.336 3(3)	0.704 6(4)
C(23)	−0.078 7(8)	−0.307 6(4)	0.663 3(4)
C(24)	−0.091 6(8)	−0.232 5(4)	0.652 2(3)
C(25)	0.030 3(7)	−0.183 9(3)	0.684 6(3)
C(26)	0.477 2(6)	−0.205 5(3)	0.815 7(2)
C(27)	0.589 9(8)	−0.247 9(3)	0.782 0(3)
C(28)	0.712 7(8)	−0.295 3(3)	0.814 5(3)
C(29)	0.726 3(8)	−0.301 2(4)	0.878 8(3)
C(30)	0.619 1(9)	−0.259 9(4)	0.912 2(3)
C(31)	0.494 9(7)	−0.211 3(3)	0.881 0(3)
C(32)	0.546(2)	0.071 5(7)	0.964 5(6)
C(33)	0.620(1)	0.134 6(5)	0.931 0(5)
O(3)	0.483 9(9)	0.170 8(4)	0.896 4(5)

Table 2 Selected bond and torsional angles (°) for complex **5**

C(1)–Fe(1)–C(7)	95.0(2)
Fe(1)–C(1)–O(1)	118.3(4)
C(7)–Fe(1)–P(1)	92.8(2)
O(1)–C(1)–C(2)	115.7(5)
C(1)–Fe(1)–P(1)	90.3(2)
C(2)–C(3)–N(1)	124.6(5)
C(3)–N(1)–C(4)	117.7(5)
N(1)–C(4)–C(5)	112.3(5)
C(4)–C(5)–C(6)	123.6(6)
C(5)–C(6)–C(2)	111.5(5)
C(6)–C(2)–C(3)	120.3(5)
C(7)–Fe(1)–C(1)–O(1)	−142.7
P(1)–Fe(1)–C(1)–O(1)	−49.9
Fe(1)–C(1)–C(2)–C(3)	16.0
C(1)–C(2)–C(3)–N(1)	176.6
C(1)–C(2)–C(6)–C(5)	−176.9
O(1)–C(1)–C(2)–C(3)	−163.5
O(1)–C(1)–C(2)–C(6)	11.0

5 revealed that the *pro-R* hydrogen (δ 2.35) had been principally replaced by deuterium, indicating that the deuteride was predominantly delivered, as might be expected, to the top unblocked face of the pyridinium complex **4**.

When a solution of ethyl benzoylformate in dry acetonitrile was treated with a stoicheiometric amount of magnesium perchlorate and complex **5** the corresponding mandelate was obtained after 21 h in 29% yield indicating that the reduction was still possible with incorporation of the bulky iron auxiliary $[Fe(\eta^5\text{-}C_5H_5)(CO)(PPh_3)]$ at C-3 of the nicotinoyl moiety.

Having developed an efficient synthesis of complex **5** and demonstrated its reactivity as a NADH mimic we turned our attention to the problem of effecting the resolution of such complexes. It was considered that resolution could be achieved by the incorporation of a homochiral moiety, of known absolute

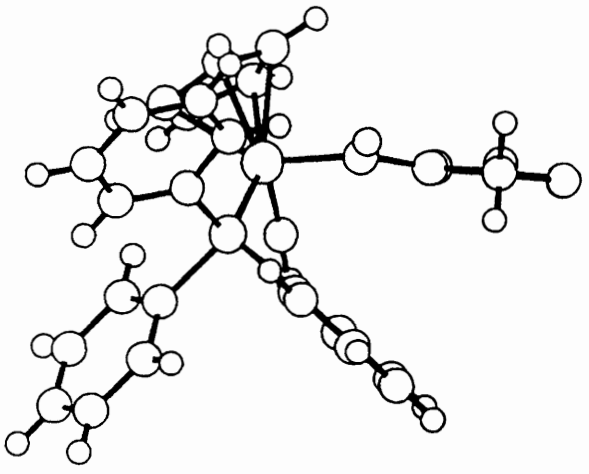


Fig. 2 Projection in the plane of the dihydronicotinoyl moiety of the molecular structure of complex **5**. Selected hydrogens on the dihydronicotinoyl moiety have been removed for clarity.

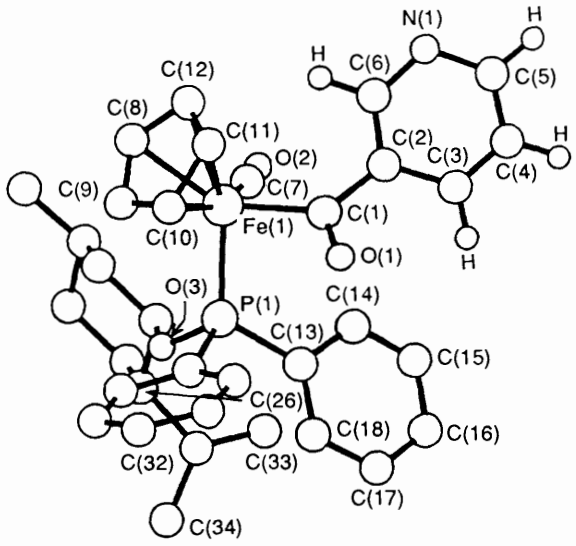
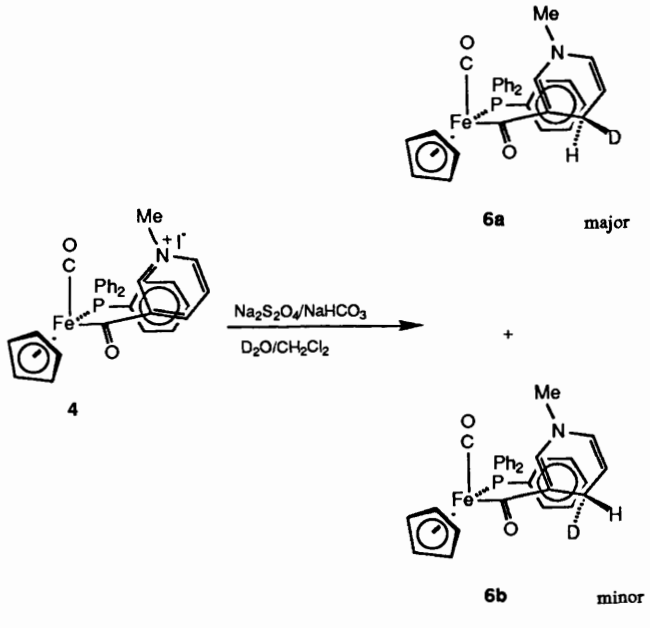


Fig. 3 The molecular structure of complex **7** as determined by X-ray crystallography showing the crystallographic numbering. All hydrogens except those on the nicotinoyl fragment have been omitted for the sake of clarity.

configuration, and separation of the resultant mixture of diastereoisomers by chromatography or crystallisation. The addition of a suitable homochiral moiety could be effected either during the photolytic step or during the formation of the pyridinium salt.

After some experimentation it was found that utilising a chiral phosphine in the photolytic step afforded a separable pair of diastereoisomers. Thus, photolytic ligand exchange of carbon monoxide in **2** for (−)-menthyl diphenylphosphinate[13] as a solution in cyclohexane afforded a 1:1 mixture of diastereoisomers **7** and **8** which were readily distinguishable by ^{1}H NMR spectroscopy. Isolation of one of the diastereoisomers was achieved by slow crystallisation from a solution in dichloromethane–heptane (*ca.* 1:5). Usually a single crystallisation gave a diastereomeric ratio of **7** and **8** greater than 100:1 and in all cases homochiral **7** $[\alpha]_D^{25}$ +155 (*c* 0.7, C_6H_6) was obtained in 11–15% yield after a second crystallisation. The assignment of the absolute configuration at iron as *R* for complex **7** follows from an *X*-ray crystal structure analysis (Fig. 3), the configuration at iron being assigned relative to the known absolute configurations within the (−)-menthyl fragment[13] this assignment is also consistent with the anomalous dispersion data. The



Scheme 2

Flack enantiopole converged to a value of 0.018(8) where a value of zero indicates the structure is of the correct absolute configuration and a value of 1 the inverse. The crystal structure reveals the pseudo-octahedral geometry around iron[12] with the nicotinoyl moiety adopting the conformation with C-4 *syn* to the nicotinoyl carbonyl oxygen. Final atomic positional coordinates are listed in Table 3 and selected bond angles and torsional angles are listed in Table 4. In this case the O(1)–C(1)–C(2)–C(3) torsional angle is 26.1° compared to 11° for the 1,4-dihydronicotinoyl complex **5**. This is clearly indicated by the conformation shown in Fig. 4 which also reveals that one face of the nicotinoyl moiety is shielded by the (−)-menthyl diphenylphosphinate ligand.

Treatment of complex **7** with iodomethane afforded, in quantitative yield, the pyridinium complex **9**, which upon reduction with sodium dithionite gave the homochiral 1,4-dihydronicotinoyl complex **10** $[\alpha]_D^{25}$ −170 (*c* 0.8, ethanol) in 73% yield (Scheme 3). The reduced complex **10** is assumed to adopt the conformation shown in Scheme 3 on the basis of an X-ray crystal structure analysis on the related racemic triphenylphosphine analogue (*R*,*S*)-[Fe(η^5-C_5H_5)(CO)(PPh_3)-(1-methyl-1,4-dihydronicotinoyl)] **5** (Fig. 1). Consistent with this conformation, the diastereotopic C-4 hydrogens exhibit significantly different chemical shifts (δ 2.98 and 2.65) in the ^{1}H NMR (300 MHz) spectrum.

When a solution of ethyl benzoylformate **11** in anhydrous acetonitrile was treated with a stoicheiometric amount of magnesium perchlorate and the homochiral complex (*R*)-(−)-**10** for 7 days at 25 °C (*R*)-(−)-ethyl mandelate **12** was isolated in 71% yield after radial chromatography. The enantiomeric excess was determined to be 52% based on the optical rotation of the ethyl mandelate $[\alpha]_D^{20}$ −53.8 (*c* 0.43, ethanol) {lit.,[14] $[\alpha]_D^{25}$ −104.4 (ethanol)}. An enantiomeric excess of 54% was indicated by analysis of the ^{19}F NMR spectrum of the corresponding (*R*)-α-(trifluoromethyl)methoxyphenylacetates.[15] When a similar experiment was undertaken in the absence of magnesium perchlorate, ethyl benzoylformate **11** was not reduced by complex *R*-(−)-**10**. Upon addition of 1 equiv. of magnesium perchlorate to complex *R*)-(−)-**10** in [$^2H_3$]acetonitrile ^{13}C NMR experiments showed a downfield shift for the signal for the C-3 carbonyl carbon of 6.3 ppm. A shift of the absorption (1600 cm^{-1}) corresponding to the stretching vibration of the C-3 carbonyl was also observed in the IR spectrum of complex

Table 3 Fractional atomic coordinates for complex **7**

Atom	*x/a*	*y/b*	*z/c*
Fe(1)	0.157 58(4)	0.010 1(2)	0.089 83(5)
P(1)	0.254 81(7)	0.085 4(2)	0.256 27(8)
O(1)	0.352 9(2)	0.037 6(4)	0.038 4(3)
O(2)	0.125 2(3)	−0.238 0(4)	0.189 2(3)
O(3)	0.203 1(2)	0.098 2(3)	0.370 6(2)
N(1)	0.226 5(3)	−0.361 1(5)	−0.123 8(4)
C(1)	0.282 6(3)	−0.038 9(5)	0.036 3(3)
C(2)	0.297 6(3)	−0.170 3(4)	−0.014 3(4)
C(3)	0.398 0(3)	−0.217 0(5)	−0.009 3(5)
C(4)	0.410 1(4)	−0.333 9(6)	−0.059 3(5)
C(5)	0.324 1(4)	−0.401 5(6)	−0.117 5(5)
C(6)	0.216 5(4)	−0.249 0(5)	−0.071 5(4)
C(7)	0.141 1(3)	−0.140 3(5)	0.150 5(4)
C(8)	−0.004 3(3)	0.051 3(5)	0.037 4(4)
C(9)	0.050 4(3)	0.160 9(5)	0.080 0(4)
C(10)	0.120 8(3)	0.189 5(5)	0.007 7(4)
C(11)	0.107 0(3)	0.095 7(6)	−0.083 2(4)
C(12)	0.031 3(3)	0.009 0(6)	−0.063 0(4)
C(13)	0.379 6(3)	0.008 5(5)	0.318 2(3)
C(14)	0.392 0(3)	−0.122 4(5)	0.302 0(4)
C(15)	0.485 6(4)	−0.183 7(5)	0.351 2(5)
C(16)	0.567 3(4)	−0.114 8(6)	0.418 0(5)
C(17)	0.556 2(3)	0.015 2(8)	0.435 3(5)
C(18)	0.462 7(3)	0.077 3(5)	0.385 8(4)
C(19)	0.286 0(3)	0.254 9(4)	0.248 2(3)
C(20)	0.229 1(3)	0.348 4(5)	0.289 4(4)
C(21)	0.242 3(4)	0.477 9(5)	0.267 5(5)
C(22)	0.313 4(4)	0.514 4(6)	0.202 5(4)
C(23)	0.372 5(4)	0.422 8(5)	0.162 5(5)
C(24)	0.359 1(3)	0.293 9(5)	0.183 8(4)
C(25)	0.156 7(3)	−0.009 5(5)	0.421 9(4)
C(26)	0.188 8(3)	0.002 7(6)	0.557 6(4)
C(27)	0.132 5(4)	−0.101 5(6)	0.613 3(5)
C(28)	0.015 3(4)	−0.093 7(7)	0.568 7(5)
C(29)	−0.017 0(4)	−0.104 1(6)	0.434 0(5)
C(30)	0.039 9(3)	−0.002 6(6)	0.375 7(4)
C(31)	−0.134 3(4)	−0.090 5(9)	0.385 5(8)
C(32)	0.307 2(3)	0.005 2(7)	0.610 1(4)
C(33)	0.335 1(4)	0.064 0(7)	0.734 9(4)
C(34)	0.358 5(5)	−0.126 3(7)	0.612 1(6)

Table 4 Selected bond and torsional angles (°) for complex **7**

C(1)–Fe(1)–P(1)	90.0(1)
C(7)–Fe(1)–P(1)	94.2(1)
C(7)–Fe(1)–C(1)	94.9(2)
O(1)–C(1)–Fe(1)	121.3(3)
C(2)–C(1)–O(1)	115.3(3)
C(3)–C(2)–C(1)	120.2(4)
C(6)–C(2)–C(1)	123.9(4)
C(6)–C(2)–C(3)	115.9(5)
C(4)–C(3)–C(2)	119.4(5)
C(5)–C(4)–C(3)	119.7(5)
C(4)–C(5)–N(1)	123.0(5)
C(2)–C(6)–N(1)	125.7(4)
C(6)–N(1)–C(5)	116.3(5)
C(7)–Fe(1)–C(1)–O(1)	−144.9
P(1)–Fe(1)–C(1)–O(1)	−50.7
Fe(1)–C(1)–C(2)–C(6)	26.7
C(1)–C(2)–C(6)–N(1)	175.4
C(1)–C(2)–C(3)–C(4)	−177.7
O(1)–C(1)–C(2)–C(6)	−151.1
O(1)–C(1)–C(2)–C(3)	26.1

R-(−)-**10** when the concentration of magnesium perchlorate was increased gradually to 1 equiv. These results indicate that not only is the presence of magnesium ion in the reaction vital for these reductions to proceed but that the magnesium ion probably chelates to *R*-(−)-**10** *via* the C-3 carbonyl oxygen.

Although the enantiomeric excess obtained in the reduction of ethyl benzoylformate utilising the homochiral complex **10** was moderate, it does serve to demonstrate that face-blocking chiral auxiliaries can be used to induce stereoselectivity in this type of reaction. It is most probably the orientation of the ketone which is poorly controlled since one face of the 1,4-dihydronicotinoyl is essentially blocked by the phosphine rotor (Fig. 2) and thus only the *pro-R* hydrogen at C-4 is free to react (Scheme 3). In line with previous models[2,5] we expected that chelation of the magnesium ion to the C-3 carbonyl oxygen and the keto and ester carbonyl oxygens of the ethyl benzoylformate will present the *Si*-face of the ketone to the C-4 *pro-R* hydrogen thus producing the mandelate (*R*)-(−)-**12** as the major enantiomer [Fig. 5(*a*)]. Delivery of the *Re*-face has been shown by molecular modelling studies to be energetically disfavoured due to steric interactions between the benzoyl-phenyl and the chiral auxiliary [Fig. 5(*b*)]. Hence, it appears that although the steric bulk of the iron auxiliary is effectively shielding one face of the 1,4-dihydronicotinoyl as predicted, it is not inducing completely stereoselective orientation, through chelation, of the substrate.

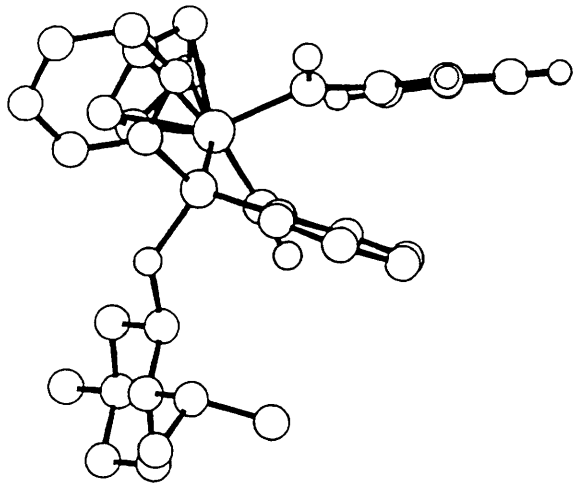
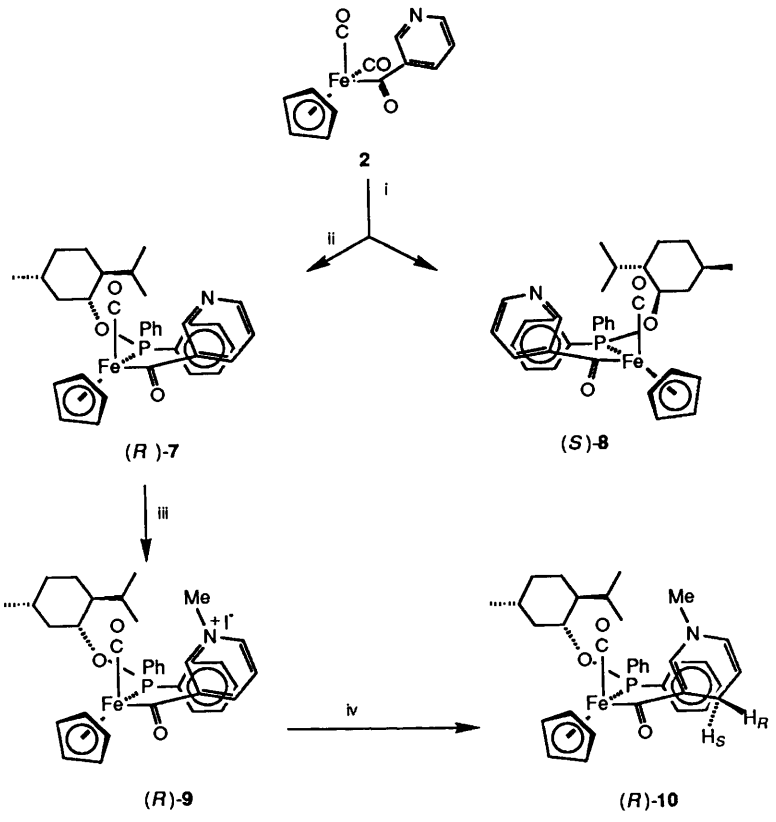


Fig. 4 Projection in the plane of the nicotinoyl moiety of the molecular structure of complex **7** with all hydrogens except those on the nicotinoyl moiety being omitted for clarity

In conclusion, we have shown that the incorporation of a sterically demanding chiral auxiliary at C-3 can be used to block selectively one face of the nicotinoyl moiety and hence induce stereoselectivity in the asymmetric reduction of a prochiral carbonyl. Combination of this effect, with a means of achieving better orientation control of the substrate, should induce a higher degree of stereoselectivity in this type of reaction. In the light of these results efforts are currently being directed towards improving this NADH mimic.

Experimental

Unless otherwise stated ^{1}H NMR spectra were recorded on a Bruker WH-300 spectrometer at 300.13 MHz and referenced to residual protio solvent with chemical shifts being reported as δ ppm from TMS. ^{13}C NMR were recorded on a Bruker AM-250 spectrometer at 62-90 MHz using $CDCl_3$ as a solvent and internal reference and are reported as δ ppm from TMS. ^{31}P NMR spectra were recorded on a Bruker AM-250 MHz spectrometer at 101.26 MHz using $CDCl_3$ as solvent and are reported as δ ppm from an external reference of triethyl phosphate in D_2O. ^{2}H NMR spectra were recorded on a Bruker AM-250 MHz spectrometer at 38.40 MHz using 1% $CDCl_3$ in $CHCl_3$ as solvent and internal standard. ^{19}F NMR spectra were recorded on a Bruker AM-250 MHz spectrometer at 235.35 MHz using $CDCl_3$ as solvent and are reported as δ ppm from an external reference of $CFCl_3$. *J* Values are recorded



Scheme 3 *Reagents and conditions:* i, $[Fe(\eta^5\text{-}C_5H_5)(CO)\{PPh_2(O\text{-}[(-)\text{-menthyl}])\}]$, cyclohexane, *hν* (54%); ii, crystallisation; iii, MeI, CH_2Cl_2 (100%); iv, $Na_2S_2O_4$, $NaHCO_3$, 0.25 mol dm^{-3} phosphate buffer, MeOH, CH_2Cl_2 (73%)

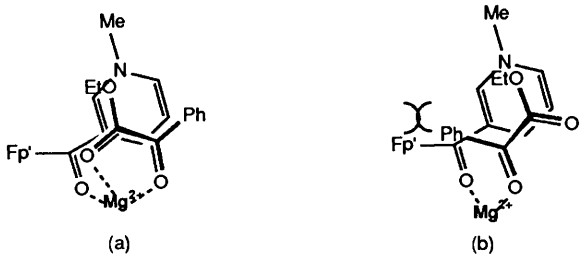


Fig. 5 Delivery of the *Si*-face (a) and *Re*-face (b) of ethyl benzoylformate to the *pro-R* hydrogen of (*R*)-(−)-$[Fe(\eta^5\text{-}C_5H_5)(CO)\{PPh_2\text{-}[O\text{-}(-)\text{-menthyl}]\}$(1-methyl-1,4-dihydronicotinoyl)] by chelation. Fp′ = $[Fe(\eta^5\text{-}C_5H_5)(CO)\{PPh_2[O\text{-}(-)\text{-menthyl}]\}$

in Hz. IR spectra were recorded in dichloromethane on a Perkin-Elmer 297 instrument. Mass spectra were recorded on a V.G. micromass ZAB 2F instrument using EI and FD techniques. Optical rotations were measured using a Perkin-Elmer 241 polarimeter. Elemental analyses were performed by the University of Manchester Analytical Service and the Dyson Perrins Laboratory Analytical Service. Gas chromatography was performed utilising a Pye 104 instrument equipped with a 10% w/w Carbowax 20M on Chromosorb W (2 m × 4 mm i.d.) column and flame ionisation detector at an oven temperature of 200 °C.

All reactions and purifications were performed under nitrogen atmosphere using standard vacuum line and Schlenk tube techniques.[16] Removal of all solvents was carried out under reduced pressure. Dichloromethane was distilled from calcium hydride and hexane refers to that fraction boiling in the range 67–70 °C. Acetonitrile was distilled from calcium hydride and then redistilled from phosphorus pentoxide. Pyridine was distilled from calcium hydride and stored over sodium hydroxide. Benzene was dried over sodium wire. Tetrahydrofuran was dried over sodium benzophenone ketyl and distilled.

Preparation of $[Fe(\eta\text{-}C_5H_5)(CO)_2(nicotinoyl)]$ **2**.—To a stirred solution of cyclopentadienyldicarbonyliron anion[8] (135.6 mmol) in tetrahydrofuran (400 ml) at −78 °C, was added a solution of freshly distilled nicotinoyl chloride[9] (21.27 g, 150.2 mmol) in tetrahydrofuran (50 ml) dropwise over 20 min. The reaction mixture was stirred for 2 h at −78 °C and then allowed to warm to room temperature and stirred overnight. Solvent was then removed, dichloromethane (500 ml) added to the residue and the resulting solution filtered through Celite. The crude product was concentrated and chromatographed over alumina (Grade 1). Elution with hexane–diethyl ether (1:1) afforded cyclopentadienyldicarbonyliron dimer as a purple solution; further elution with ethyl acetate gave a yellow solution which upon concentration afforded complex **2** (27.47 g, 72%) as a yellow solid (Found: C, 55.4; H, 3.1; N, 4.8. Calc. for $C_{13}H_9FeNO_3$: C, 55.2; H, 3.20; N, 4.95%); ν_{max}/cm^{-1} 2100 (C≡O), 1965 (C≡O) and 1600 (C=O); $\delta_H(C_6D_6)$ 9.09 (1 H, br s, 2-H), 8.49 (1 H, br d, $^3J_{HH}$ 3.7, 6-H), 7.54 (1 H, dt, $^3J_{HH}$ 7.9, $^4J_{HH}$ 2.0, 4-H), 6.70 (1 H, dd, $^3J_{HH}$ 7.9, 4.7, 5-H) and 4.04 (5 H, s, C_5H_5); δ_C 213.30 (C≡O), 150.50 (6-C), 147.29 (2-C), 145.07 (3-C), 132.31 (4-C), 123.31 (5-C) and 86.23 (C_5H_5); *m/z* 283 (M^+) and 255 (M^+ − 28).

Preparation of $[Fe(\eta^5\text{-}C_5H_5)(CO)(PPh_3)(nicotinoyl)]$ **3**.—

A suspension of finely ground complex **2** (2.66 g, 9.4 mmol) in a solution of triphenylphosphine (3.70 g, 14.1 mmol) in cyclohexane (140 ml) was irradiated internally in a quartz immersion apparatus using a Hanovia 125-W medium pressure mercury arc lamp. The reaction was monitored by IR spectroscopy (disappearance of carbonyl stretches at 2100 and 1965 cm^{-1}) and irradiation stopped after 72 h. The product, an orange precipitate which coated the walls of the reaction vessel, was filtered off, washed with cyclohexane and dissolved in dichloromethane. This solution was filtered through alumina (Grade V) and then evaporated and the residue crystallised from dichloromethane–hexane to give the title compound **3** (3.94 g, 81%) as an orange crystalline solid (Found: C, 69.4; H, 4.8; N, 2.7; P, 5.8. Calc. for $C_{30}H_{24}FeNO_2P$: C, 69.65; H, 4.7; N, 2.7; P, 6.0%); ν_{max}/cm^{-1} 1940 (C≡O) and 1580 (C=O); $\delta_H(CDCl_3)$ 8.46 (1 H, dd, $^3J_{HH}$ 4.7, $^4J_{HH}$ 1.6, 6-H), 8.20 (1 H, d, $^4J_{HH}$ 1.5, 2-H), 7.50–7.28 (15 H, m, Ph), 7.23 (1 H, dt, $^3J_{HH}$ 7.9, $^4J_{HH}$ 1.9, 4-H), 7.12 (1 H, dd, $^3J_{HH}$ 7.9, 4.8, 5-H) and 4.59 (5 H, d, $^3J_{PH}$ 1.3, C_5H_5); δ_C 220.43 (d, $^2J_{PC}$ 31.6, C≡O), 149.46 (s, 6-C), 147.30 (s, 2-C), 146.61 (s, 3-C), 135.85 (d, $^1J_{PC}$ 43.6, Ph C_{ipso}), 133.31 (d, $^2J_{PC}$ 9.8, Ph C_{ortho}), 132.64 (s, 4-C), 129.87 (s, Ph C_{para}), 128.13 (d, $^3J_{PC}$ 9.4, Ph C_{meta}), 122.43 (s, 5-C) and 85.39 (s, C_5H_5); δ_P 70.66; *m/z* 517 (M^+).

Preparation of [Fe(η^5-C_5H_5)(CO)(PPh_3)(1-*methyl*-1,4-*dihydronicotinoyl*)] **5**.—To an orange solution of complex **3** (1.368 g, 2.65 mmol) in dichloromethane (60 ml) was added iodomethane (4 ml) and the reaction mixture stirred at room temperature for 18 h. Concentration afforded the crude pyridinium salt **4** (100%) as an orange–brown amorphous solid; ν_{max}/cm^{-1} 1920 (C≡O) and 1560 (C=O); $\delta_H(CD_2Cl_2)$ 9.27 (1 H, d, $^3J_{HH}$ 5.9, 6-H), 8.01 (1 H, d, $^3J_{HH}$ 8.0, 4-H), 7.90 (1 H, dd, $^3J_{HH}$ 7.9, 5.9, 5-H), 7.52–7.35 (15 H, m, Ph), 7.25 (1 H, s, 2-H), 4.74 (5 H, d, $^3J_{PH}$ 1.0, C_5H_5) and 4.40 (3 H, s, Me); *m/z* 532 (M^+ of cation).

The pyridinium salt **4** was dissolved in a mixture of methanol (20 ml) and dichloromethane (80 ml) and added to a solution of a sodium dithionite (85%; 5.00 g, 24.41 mmol) and sodium hydrogen carbonate (3.00 g, 35.71 mmol) in distilled water (60 ml) and stirred vigorously for 16 h in the dark. The organic layer was separated, the aqueous layer washed with dichloromethane (2 × 30 ml) and the combined organic fractions were concentrated. Chromatography of the concentrate over alumina (Grade V) afforded complex **5** (1.21 g, 85%) which crystallised from ethanol–hexane (*ca.* 1:5) as red solid containing one equivalent of ethanol (Found: C, 69.7; H, 5.75; N, 2.2; P, 5.3. Calc. for $C_{31}H_{28}FeNO_2P + C_2H_6O$: C, 69.4; H, 5.9; N, 2.4; P, 5.35%); ν_{max}/cm^{-1} 1905 (C≡O), 1740 (C=O) and 1600 (C=O); $\delta_H(CDCl_3)$ 7.58–7.30 (15 H, m, Ph), 6.98 (1 H, d, $^4J_{HH}$ 1.4, 2-H), 5.67 (1 H, dd, $^3J_{HH}$ 7.9, $^4J_{HH}$ 1.5, 6-H), 4.65 (1 H, dt, $^3J_{HH}$ 7.9, 4.2, 5-H), 4.42 (5 H, d, $^3J_{PH}$ 1.2, C_5H_5), 3.05 (3 H, s, Me), 2.92 (1 H, br d part of AB system, $^2J_{HH}$ 19.2, *pro R* 4-H) and 2.35 (1 H, br d part of AB system, $^2J_{HH}$ 19.2, *pro S* 4-H); δ_C 222.44 (d, $^2J_{PC}$ 36.3, C≡O), 147.31 (s, 2-C), 137.11 (d, $^1J_{PC}$ 42.1, Ph C_{ipso}), 133.46 (d, $^2J_{PC}$ 9.3, Ph C_{ortho}), 129.43 (s, 6-C), 129.39 (c, Ph C_{para}), 127.88 (d, $^3J_{PC}$ 9.5, Ph C_{meta}), 124.84 (s, 3-C), 105.23 (s, 5-C), 85.17 (s, C_5H_5), 41.07 (s, Me) and 24.06 (s, 4-C); δ_P 73.38; *m/z* 533 (M^+).

Preparation of [Fe(η^5-C_5H_5)(CO)(PPh_3)(1-*methyl*-4-*deuterio*-1,4-*dihydronicotinoyl*)] **6**.—A solution of the pyridinium salt **4** (0.375 g, 0.57 mmol) in dichloromethane (30 ml) was added to a solution of sodium dithionite (85%; 1.00 g, 4.88 mmol) and sodium hydrogen carbonate (0.60 g, 7.14 mmol) in deuterium oxide (20 ml) and the reaction mixture stirred vigorously in the dark for 12 h. The reaction mixture was worked up as described above (for the preparation of **5**) to afford the deuteriated complex **6** (0.228 g, 75%) as an orange solid; ν_{max}/cm^{-1} 1905 (C≡O), 1740 (C=O) and 1600 (C=O); $\delta_H(CDCl_3)$ 7.60–7.30 (15 H, m, Ph), 7.00 (1 H, d, $^4J_{HH}$ 1.2, 2-H), 5.68 (1 H, dt, $^3J_{HH}$ 7.9, $^4J_{HH}$ 1.5, 6-H), 4.65 (1 H, dd, $^3J_{HH}$ 7.9, 3.5, 5-H), 4.44 (5 H, d, $^3J_{PH}$ 0.7, C_5H_5), 3.04 (3 H, s, Me) and 2.34 (0.8 H, s, *pro S* 4-H); $\delta_D(CHCl_3)$ 2.92 (0.8 D, br s, *pro R* 4-D) and 2.34 (0.2 D, br s, *pro R* 4-H); *m/z* 534 (M^+).

Preparation of (R)-(+)-[Fe(η^5-C_5H_5)(CO){PPh_2(O-[(−)-*menthyl*])}(*nicotinoyl*)] **7**.—A solution of the iron complex **2** (3.60 g, 12.7 mmol) and diphenylphosphinic acid (−)-menthyl ester[13] (6.00 g, 16.0 mmol) in dichloromethane (70 ml) was irradiated internally in a quartz immersion apparatus using a Hanovia 125-W medium pressure mercury arc lamp. The reaction was monitored by IR spectroscopy (disappearance of carbonyl stretches at 2100 and 1965 cm^{-1}) and stopped after 5 h. Longer reaction times resulted in a significant amount of the product undergoing decarbonylation. The reaction mixture was concentrated and chromatographed over alumina (Grade V) to give unchanged phosphinic ester, on elution with hexane, followed by a 1:1 mixture of the diastereoisomeric complexes **7** and **8** (4.12 g, 54%), on elution with diethyl ether. A final band of unchanged complex **2** (1.58 g, 44%) was collected, on elution with dichloromethane. Complexes **7** and **8** were crystallised slowly from a solution of dichloromethane–heptane (*ca.* 1.5) at −20 °C to give **7** (0.86 g, 11%, d.e. better than 150:1 by ^{31}P NMR) as an orange crystalline solid; $[\alpha]^{27}_{546}$ +204.5, $[\alpha]^{27}_{578}$ +154.9, $[\alpha]^{27}_{589}$ +142.5 (*c* 0.07, C_6H_5) (Found: C, 68.4; H, 6.5; N, 2.3; P, 5.2. Calc. for $C_{34}H_{38}FeNO_3P$: C, 68.6; H, 6.4; N, 2.35; P, 5.2); ν_{max}/cm^{-1} 1920 (C≡O) and 1585 (C=O); $\delta_H(CDCl_3)$ 8.49 (2 H, br s, 2-H and 6-H), 8.10 (2 H, m, Ph), 7.53 (3 H, m, Ph), 7.47 (1 H, dt, $^3J_{HH}$ 7.8, $^4J_{HH}$ 1.8, 4-H), 7.29 (1 H, br dd, $^3J_{HH}$ 7.7, 4.4, 5-H), 7.21 (5 H, m, Ph), 4.55 (5 H, d, $^3J_{PH}$ 1.2, C_5H_5), 3.75 (1 H, ddt, $^3J_{PH}$ 8.0, $^3J_{HH}$ 10.5, 4.1, POCH), 1.98 (1 H, m, cyclohexyl H), 1.70–0.77 (8 H, m, cyclohexyl H), 0.86 (3 H, d, $^3J_{HH}$ 6.5, Me), 0.67 (3 H, d, $^3J_{HH}$ 7.0, Me) and 0.17 (3 H, d, $^3J_{HH}$, 6.9, Me); $\delta_C(CDCl_3)$ 271.19 (d, $^2J_{PC}$ 26.0, C=O), 221.11 (d, $^2J_{PC}$ 35.4, C≡O), 149.57 (s, 6-C), 147.46 (s, 2-C), 146.99 (s, 3-C), 139.87 (d, $^1J_{PC}$ 47.8, Ph C_{ipso}), 139.77 (d, $^1J_{PC}$ 49.3, Ph C_{ipso}), 132.69 (s, 4-C), 132.25 (d, $^2J_{PC}$ 11.1, Ph C_{ortho}), 131.58 (d, $^2J_{PC}$ 11.1, Ph C_{ortho}), 130.36 (s, Ph C_{para}), 130.08 (s, Ph C_{para}), 127.86 (d, $^3J_{PC}$ 9.5, Ph C_{meta}), 127.60 (d, $^3J_{PC}$ 9.5, Ph C_{meta}), 122.82 (s, 5-C), 85.88 (s, C_5H_5), 77.92 (d, $^2J_{PC}$ 6.9, POCH), 49.64 (d, $^3J_{PC}$ 5.4, POCHCH), 43.89 (s, CH_2), 34.06 (s, CH_2), 31.65 (s, CH), 24.86 (s, CH), 22.90 (s, CH_2), 22.16 (s, Me), 21.36 (s, Me) and 15.29 (s, Me); δ_P 164.85; *mz* 595 (M^+).

Preparation of (R)-(+)-[Fe(η^5-C_5H_5)(CO){PPh_2(O-[(−)-*menthyl*])}(1-*methylnicotinoyl*)] *Iodide* **9**.—To a solution of complex **7** (0.632 g, 0.106 mmol) in dichloromethane (15 ml) was added iodomethane (2 ml) and the solution was stirred for 18 h at room temperature. Removal of solvent and drying gave pure complex **9** (0.781 g, 100%) as an orange amorphous solid, $[\alpha]^{26}_{546}$ 353.9, $[\alpha]^{26}_{578}$ +250.9, $[\alpha]^{26}_{589}$ +233.0 (*c* 0.05, acetone) (Found: C, 56.75; H, 5.7; N, 1.8. Calc. for $C_{35}H_{41}FeINO_3P$: C, 57.0; H, 5.6; N, 1.9); ν_{max}/cm^{-1} 1925 (C≡O) and 1560 (C=O); $\delta_H(CDCl_3)$ 9.47 (1 H, d, $^3J_{HH}$ 5.9, 6-H), 8.03 (2 H, m, Ph), 7.98 (1 H, d, $^3J_{HH}$ 8.0, 4-H), 7.89 (1 H, dd, $^3J_{HH}$ 8.0, 5.9, 5-H), 7.76 (1 H, s, 2-H), 7.58 (3 H, m, Ph), 7.40–7.05 (5 H, m, Ph), 4.77 (5 H, d, $^3J_{PH}$ 1.2, C_5H_5), 4.56 (3 H, s, NCH_3), 3.78 (1 H, ddt, $^3J_{PH}$ 6.9, $^3J_{HH}$ 10.5, 4.1, POCH), 1.82 (1 H, m, cyclohexyl H), 1.68–0.78 (8 H, m, cyclohexyl H), 0.84 (3 H, d, $^3J_{HH}$ 6.5, Me), 0.73 (3 H, d, $^3J_{HH}$ 7.0, Me) and 0.38 (3 H, d, $^3J_{HH}$ 6.9, Me); δ_C 275.88 (d, $^2J_{PC}$ 28.4, C=O), 220.36 (d, $^2J_{PC}$ 34.0, C≡O), 148.81 (d, $^3J_{PC}$ 6.8, 3-C), 144.23 (s), 141.14 (s), 140.76 (s), 140.14 (d, $^1J_{PC}$ 52.9, Ph C_{ipso}), 138.26 (d, $^1J_{PC}$ 44.8, Ph C_{ipso}), 132.49 (d, $^2J_{PC}$ 11.3, Ph C_{ortho}), 131.23 (s, Ph C_{para}), 131.07 (d, $^2J_{PC}$ 10.3, Ph C_{ortho}), 130.38 (s, Ph C_{para}), 128.37 (d, $^3J_{PC}$ 10.4, Ph C_{meta}), 127.95 (d, $^3J_{PC}$ 9.5, Ph C_{meta}), 127.54 (s, 5-C), 86.51 (s, C_5H_5), 79.20 (d, $^2J_{PC}$ 7.5, POCH), 49.75 (d, $^3J_{PC}$ 6.0, POCHCH), 49.46 (s, NMe), 44.13

(s, CH_2), 34.00 (s, CH_2), 31.88 (s, CH), 24.98 (s, CH), 22.93 (s, CH_2), 21.92 (s, Me), 21.25 (s, Me) and 15.36 (s, Me); δ_P 161.97; *m/z* 610 (M^+ of cation).

Preparation of (R)-(−)-[Fe(η^5-C_5H_5)(CO){PPh_2(O-[(−)-*menthyl*])}(1-*methyl*-1,4-*dihydronicotinoyl*)] **10**.—A solution of the pyridinium complex **9** (0.721 g, 1.03 mmol) in dichloromethane (30 ml) was added to a solution of sodium dithionite (85%; 2.50 g, 12.20 mmol) in 0.25 mol dm^{-3} phosphate buffer pH 7 (30 ml) and the mixture was stirred for 36 h in the dark. The organic layer was separated, the aqueous layer was washed with dichloromethane (2 × 30 ml) and the combined organic fractions were concentrated. A solution of the crude product in dichloromethane was filtered through a short plug of alumina (Grade V) to afford complex **10** (0.461 g, 73%) as an orange solid, $[\alpha]_{546}^{23}$ −129.9, $[\alpha]_{578}^{23}$ −107.3, $[\alpha]_{589}^{23}$ −103.9 (*c* 0.12, acetone); ν_{max}/cm^{-1} 1905, 1670 and 1600; $\delta_H(CDCl_3)$ 8.16 (2 H, m, Ph), 7.52–7.18 (8 H, m, Ph), 7.15 (1 H, d, $^4J_{HH}$ 1.5, 2-H), 5.71 (1 H, dd, $^3J_{HH}$ 7.9, $^4J_{HH}$ 1.6, 6-H), 4.71 (1 H, dt, $^3J_{HH}$ 7.5, 3.7, 5-H), 4.35 (5 H, d, $^3J_{HH}$ 1.2, C_5H_5), 3.79 (1 H, ddt, $^3J_{PH}$ 9.2, $^3J_{HH}$ 10.1, 4.0, POCH), 3.09 (3 H, s, NMe), 2.98 (1 H, br d part of AB system, $^2J_{HH}$ 17.6, *pro-R* 4-H), 2.64 (1 H, br d part of AB system, $^2J_{HH}$ 17.6, *pro-S* 4-H), 2.18 (1 H, m, cyclohexyl H), 1.65–0.73 (8 H, m, cyclohexyl H), 0.90 (3 H, d, $^3J_{HH}$ 6.6, Me), 0.64 (3 H, d, $^3J_{HH}$ 7.0, Me) and 0.01 (3 H, d, $^3J_{HH}$ 6.8, Me); δ_C 261.99 (d, $^2J_{PC}$ 21.9, C=O), 223.28 (d, $^2J_{PC}$ 38.3, C≡O), 147.49 (s, 2-C), 142.03 (d, $^1J_{PC}$ 50.4, Ph C_{ipso}), 140.22 (d, $^1J_{PC}$ 44.1, Ph C_{ipso}), 132.28 (d, $^2J_{PC}$ 11.2, Ph C_{ortho}), 131.88 (d, $^2J_{PC}$ 10.2, Ph C_{ortho}), 129.79 (s), 129.49 (s), 129.42 (s), 127.48 (d, $^3J_{PC}$ 8.5, Ph C_{meta}), 127.35 (d, $^3J_{PC}$ 8.3, Ph C_{meta}), 124.52 (d, $^3J_{PC}$ 3.8, 3-C), 105.32 (s, 5-C), 85.85 (s, C_5H_5), 76.43 (d, $^2J_{PC}$ 5.3, POCH), 49.75 (d, $^3J_{PC}$ 4.6, POCHCH), 43.62 (s, CH_2), 41.09 (s, NMe), 34.21 (s, CH_2), 31.54 (s, CH), 24.93 (s, CH), 24.31 (s, 4-C), 22.95 (s, CH_2), 22.29 (s, Me), 21.45 (s, Me) and 15.04 (s, Me); δ_P 166.21 (Found: M^+, 611.2265. $C_{35}H_{42}FeNO_3P$ requires *M*, 611.2253).

Reduction of Ethyl Benzoylformate by Complex **5**.—To a solution of ethyl benzoylformate (28.9 mg, 0.162 mmol) in dry acetonitrile (3 ml) was added complex **5** (90.2 mg, 0.169 mmol), followed by magnesium perchlorate (32.3 mg, 0.145 mmol) and 4-A molecular sieves (*ca.* 15). The solution was stirred under nitrogen in the dark and followed by gas chromatography. After 21 h the solvent was carefully removed under reduced pressure and the residue extracted with diethyl ether (3 × 3 ml). Radial chromatography (1 mm thick silica gel plate) gave unchanged ethyl benzoylformate (on elution with 20% diethyl ether–hexane) followed by ethyl mandelate (on elution with 40% diethyl ether–hexane) (8.7 mg, 29%), which was determined to be pure by gas chromatography and by comparison of the ^1H NMR spectrum with that of an authentic sample.

Reduction of Ethyl Benzoylformate **11** *by Complex* **10**.—To a solution of ethyl benzoylformate (34.5 mg, 0.19 mmol) in dry acetonitrile (3 ml) was added complex **10** (110 mg, 0.18 mmol), followed by magnesium perchlorate (51.6 mg, 0.21 mmol) and 4-A molecular sieves (*ca.* 20). The solution was stirred under nitrogen in the dark at room temperature and the reaction followed by gas chromatography. After 7 days water (0.1 ml) was added and the solvent was carefully removed under reduced pressure. The residue was extracted with diethyl ether (3 × 3 ml) and filtered through a short plug of flash silica gel. Radical chromatography (2 mm thick silica gel plate) gave unchanged ethyl benzoylformate **11** (on elution with 20% diethyl ether–hexane) followed by ethyl mandelate (on elution with 40% diethyl ether–hexane) (23.2 mg, 71%), which was determined to be pure by gas chromatography and by comparison of the ^1H NMR spectrum with that of an authentic sample; $[\alpha]_D^{20}$ −53.8 (*c* 0.43, ethanol) {lit.,[14] $[\alpha]_D^{20}$ −104.4 (ethanol)}; which corresponds to a 52% ee of the mandelate (*R*)-(−)-**12**.

To a solution of the ethyl mandelate in dry pyridine (3 ml) at 0 °C was slowly added a solution of (*S*)-(+)-α-methoxy-α-(trifluoromethyl)phenylacetyl chloride[17] in dry benzene (2 ml). The resulting mixture was allowed to warm to room temperature and then stirred overnight. Dichloromethane (10 ml) was added and the organic fraction was washed with water (2 × 5 ml) and brine (2 × 5 ml) and dried (K_2CO_3). Filtration and removal of solvent gave the crude derivative; δ_F −73.6 (*S,R*) and −73.9 (*S,S*) in a relative proportion of 77:23 which corresponds to 54% ee of the mandelate (*R*)-(−)-**12**.

Crystal Structure Determinations

Crystal Data for **5**.—$C_{31}H_{28}FeNO_2P{\cdot}C_2H_5OH$, M_r = 533.39, monoclinic, $P2_1/c$ (No. 14), a = 7.766(2), b = 17.901(3), c = 21.308(4) Å, β = 97.71(4)° (from least squares fitting of setting angles for 25 reflections), V = 2935 Å^3, Z = 4, D_x = 1.31 g cm^{-3}, Cu-Kα radiation (graphite monochromated), μ = 48.49 cm^{-1}, crystal dimensions 0.4 × 0.4 × 0.8 mm.

Data collection and processing. Data were collected on a CAD-4F diffractometer in ω:2θ mode, $0 < 2\theta \leq 150°$. 7646 Reflections were measured, 3753 unique (R_{merge} = 0.029) of which 3676 were observed ($I \geq 3\sigma I$). No significant variation in intensity of 3 check reflections was observed. Data were corrected for Lorentz and polarization effects[18] and an absorption correction based on azimuthal scans (min. = 1.00, max. = 1.08) was employed.[19]

Structure solution and refinement. The structure was solved by direct methods,[20] atoms not found in the initial solution were located in subsequent Fourier maps.[18] Refinement of the model was undertaken using the CRYSTALS program package.[18] Full matrix least-squares refinement of positional and anisotropic thermal parameters for all non-hydrogen atoms was continued until covergence (rms shift/esd < 0.01), the H-atom coordinates were geometrically calculated and included in the model together with arbitrary isotropic thermal parameters. The solvating ethanol molecule has high thermal parameters, possibly due to unresolved disorder and the molecule was included in the model but was restrained to have 'normal' bond lengths and angles. A short O–O separation of 2.775(6) Å is observed between the acyl and ethanol oxygens consistent with a hydrogen bonding interaction. A 3-term Chebychev polynomial weighting scheme[21] was employed and a correction for extinction was made.[22] At convergence R = 0.067, R_w = 0.091 [$R = \Sigma w|\Delta|(\Sigma wF_o)^{-1}$, $R_w = \Sigma w\Delta_i^2(\Sigma wF_{oi}^2)^{-1}$].

Crystal Data for **7**.—$C_{34}H_{38}FeNO_3P$, M = 595.5, monoclinic, $P2_1$ (No. 4), a = 13.220(2), b = 10.385(2), c = 11.487(2) Å, β = 103.38(1)° (from least squares fitting of setting angles for 25 reflections), U = 1534 Å^3, Z = 2, D_x = 1.29 g cm^{-3}, Cu-Kα radiation (graphite monochromated), μ = 47.11 cm^{-1}, crystal dimensions 0.5 × 0.5 × 0.7 mm.

Data collection and processing. Data were collected on a CAD-4F diffractometer in ω:2θ mode, $0 < 2\theta \leq 140°$. 3636 Reflections measured, 2912 unique (R_{merge} = 0.034) of which 2600 were observed ($I \geq 3\sigma I$). No significant variation in intensity of 3 check reflections was observed. Data were corrected for Lorentz and polarization effects[18] and an absorption correction based on azimuthal scans (min. = 3.79, max. = 7.77) was employed.[19]

Structure solution and refinement. The structure was solved by Patterson techniques[23] and refinement of the model was undertaken using the CRYSTALS program package.[18] Full matrix least-squares refinement of positional and anisotropic thermal parameters for all non-hydrogen atoms, a Flack

enantiopole[24] and isotropic thermal parameters for each H-atom type was continued until convergence (rms shift/esd < 0.01), the H-atom coordinates were geometrically calculated. A 3-term Chebychev polynomial weighting scheme[21] was employed and a correction for extinction was made.[22] At convergence $R = 0.034$, $R_w = 0.041$ [R, R_w as for **5**] and the Flack enantiopole = 0.018(8). The assignment of N(1) and C(4) atom types was based initially on peak sizes. The refined thermal parameters of these atoms are of similar magnitude, whereas refinement of the alternate assignment leads to dissimilar values [C(4) lower, N(1) higher], this supports the assignment as given.

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