# Functional-Group Attachment and Interconversion at a Chiral [3]Ferrocenophane Framework

Christian Nilewski, Markus Neumann, Ludger Tebben, Roland Fröhlich, Gerald Kehr, Gerhard Erker*

Organisch-Chemisches Institut, Universität Münster, Corrensstrasse 40, 48149 Münster, Germany
Fax +49(251)8336503; E-mail: erker@uni-muenster.de

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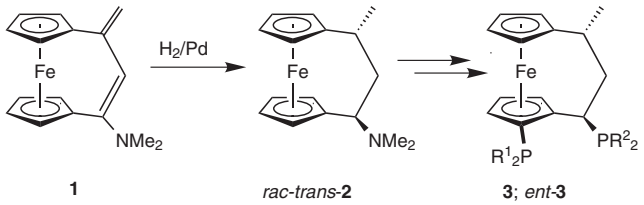
Dedicated to Professor Dieter Hoppe on the occasion of his 65th birthday

**Abstract:** Mannich condensation of 1,1′-diacetylferrocene with dimethylamine followed by catalytic hydrogenation gives the chiral α-dimethylamino[3]ferrocenophane. Both enantiomers are available by resolution. Directed *ortho*-lithiation/iodination yields the *ortho*-iodo-α-dimethylamino[3]ferrocenophane derivative, whose treatment with acetic anhydride and copper(I) oxide yielded the mono- and diacetoxy-functionalized derivatives. The *ortho*-phosphorylated α-dimethylamino systems (-$PPh_2$, -$PCy_2$) underwent exchange of the directing $NMe_2$ group with $NH_2$ by means of an ammonolysis reaction of the corresponding α-chloride derivatives, which in turn were obtained by treatment of the α-dimethylamino compounds with methylchloroformate. Starting from α-dimethylamino[3]ferrocenophane, the sequence of directed *ortho*-lithiation (*t*-BuLi), treatment with *p*-tosyl azide/sodium pyrophosphate (to yield the *ortho*-azido[3]ferrocenophane derivative) followed by catalytic hydrogenation gave the *ortho*-amino and α-dimethylamino[3]ferrocenophane derivatives. The potential use of some of the chelate ferrocenophane ligands in Ru-catalyzed asymmetric hydrogenations was investigated. Seven of the newly synthesized compounds were characterized by X-ray diffraction.

**Key words:** ferrocene, chelate ligand, amino group, P,N-ligand, asymmetric hydrogenation, catalysis

Recently ferrocene-based chelate ligands have gained considerable importance in catalytic developments.[1] Of the various ferrocene-derived backbone structures the [3]ferrocenophanes seem to be useful for the construction of chelate ligands[2] for some interesting specific purposes. We recently found that palladium catalysts derived from the bisphosphino[3]ferrocenophane chelates **3** show a remarkable catalyst performance in alternating olefin/carbonmonoxide polymerization.[3] With some such systems very high catalyst reactivities were achieved and the main chain chirality alternating (propene–*co*–CO) copolymer[4,5] was formed with high asymmetric induction.[6]




**1** *rac-trans*-**2** **3**; *ent*-**3**

**Scheme 1**

We recently introduced a very convenient synthetic entry to such bisphosphino[3]ferrocenophane chelate ligand chemistry, which was based on the intramolecular Mannich condensation reaction of 1,1′-diacetylferrocene with dimethylamine to yield **1**.[7,8] Subsequent hydrogenation gave the *trans*-disubstituted dimethylamino[3]ferrocenophane **2** as the major product.[9] We developed a simple and effective chiral auxiliary-based racemate cleavage procedure at this stage, which gave the pure enantiomers (*R*,*R*)-**2** and (*S*,*S*)-**2** readily in high yield as synthetic building blocks for further chiral chelate ligand syntheses.[10] The enantiomerically pure ligands of type **3** were eventually prepared from **2**.[3,6]

The successful use of ligands **3** in asymmetric catalysis prompted us to initiate the development of further catalysts based on this functional [3]ferrocenophane. It turned out that the [3]ferrocenophane systems required the application and development of some specific reaction sequences to allow an easy and selective attachment of various functional groups at the required positions of the framework. Here we briefly outline and report selected examples that have led to the introduction of oxygen functionalities and the regio- and stereoselective attachment of amino groups. Some of the latter systems were tested for their potential use in the Ru-catalyzed asymmetric reduction of aryl ketone model compounds.

## Introduction of Oxygen Functionalities

We chose the acetate function as the oxygen functionality to be selectively attached to the [3]ferrocenophane framework. All of these reactions were carried out with only racemic compounds. Principally a variety of donor substituents at the α-position of the $C_3$-bridge of the [3]ferrocenophane could be used to effect a directed functionalization at the 2-position of its adjacent Cp ring. It has turned out that the dimethylamino substituent was by far the best for that purpose.

Therefore, we treated the dimethylamino[3]ferrocenophane system **2** with *tert*-butyl lithium in diethyl ether. The resulting lithiated product **4** was not isolated but generated in situ and then directly quenched by treatment with iodine to give the iodo derivative **5** (isolated in ca. 50% yield). Compound **5** was then treated with acetic anhydride in acetonitrile in the presence of copper(I) ox-

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ide in a one-pot procedure that eventually resulted in the replacement of both the dimethylamino and the iodide substituents by acetate. The reaction takes place stepwise; metal-assisted nucleophilic substitution[11,12] of the α-dimethylamino substituent is fast and occurs by a double inversion process resulting in the formation of **7** with retention of stereochemistry. From a reaction that was stopped after a reaction time of six hours we were able to obtain single crystals of the intermediate product **7** that were characterized by X-ray diffraction. The oxidative replacement of iodide at the ferrocene nucleus[13] was much slower. It required a total reaction time of 16 hours at reflux temperatures to go to completion. The diacetoxy-substituted [3]ferrocenophane product *rac*-**8** was eventually isolated in close to quantitative yield (Scheme 2).

Complex **5** shows the typical $^1$H NMR spectral features for the protons at the strongly folded $C_3$-bridge, which leads to a pronounced differentiation of the pseudo-axial and pseudo-equatorial hydrogen resonances [i.e., 2.84 (8-$H_{ax}$), 2.25 (8-$H_{eq}$), 2.79 (9-H) ppm]. The X-ray crystal structure analysis (Figure 1) shows the presence of a chair-like conformation for the $C_3$-bridge at the ferrocenophane nucleus. The larger bridge substituent of *rac-trans*-**5**, namely the dimethylamino group at C9, is oriented in a pseudo-equatorial position, whereas the smaller methyl group at C6 is oriented pseudo-axially. This has resulted in a practically undisturbed arrangement of the ferrocene moiety, which is found in a nearly eclipsed metallocene conformation. The ferrocene C14–I and the bridge C9–$NMe_2$ vectors are found in a close to gauche conformational orientation.

Single crystals of the α-acetoxy functionalized system **7** were obtained from dichloromethane. The X-ray crystal structure analysis (Figure 2) shows the typical chair-like conformation of the $C_3$-bridged framework with the acetoxy substituent oriented in a pseudo-equatorial position at the bridge and the methyl group at C6 oriented in a pseudo-axial position. The bulk of this substituent is consequently oriented away from the core of the ferrocene framework.

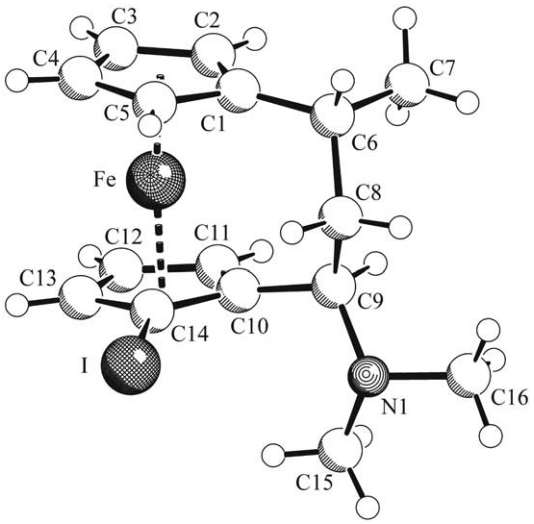
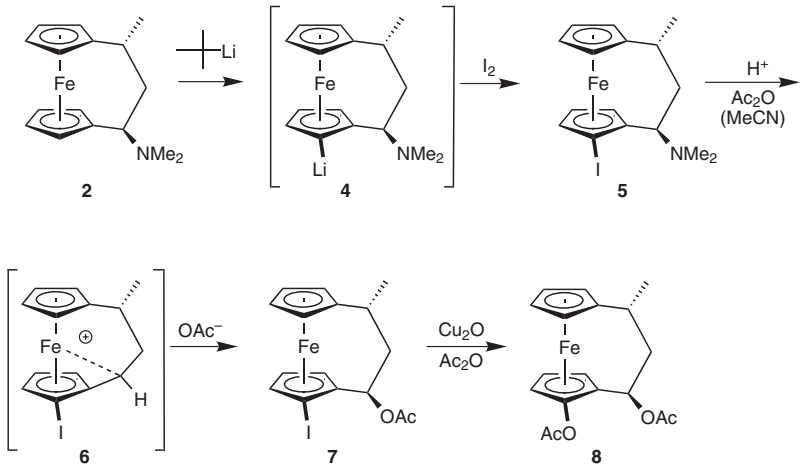



**Figure 1** A view of the molecular structure of complex *rac-trans*-**5**. Selected bond lengths (Å) and angles (°): Fe–C1 2.020(2), Fe–C2 2.036(2), Fe–C3 2.049(2), Fe–C4 2.047(2), Fe–C5 2.026(2), Fe–C10 2.012(2), Fe–C11 2.035(2), Fe–C12 2.059(2), Fe–C13 2.048(2), Fe–C14 2.021(2), C14–I 2.085(2), C9–C10 1.511(3), C9–N1 1.481(3), C8–C9–C10 112.7(2), C6–C8–C9 115.9(2), C1–C6–C8 112.6(2).

The diacetyl-substituted compound **8** features a similar structure in the crystal (see Figure 2, bottom). The oxygen atom O1 in this case must reside in the Cp plane but the adjacent –$COCH_3$ moiety is again oriented away from the ferrocene core.

## Attachment of $NH_2$ Groups

The selective attachment of $NH_2$ groups to the chiral [3]ferrocenophane framework proved to be slightly more difficult. We first developed a viable synthetic pathway to replace the $NMe_2$ substituent in compounds **9** (which in turn were readily obtained by treatment of **4** with either $ClPPh_2$ or $ClPCy_2$)[3,6] by $NH_2$. We first tried this by a variation of the established route,[10] i.e. by exchange with a benzylic amine followed by reductive cleavage. This proved to be synthetically unfavorable. However, the fol-




**Scheme 2**

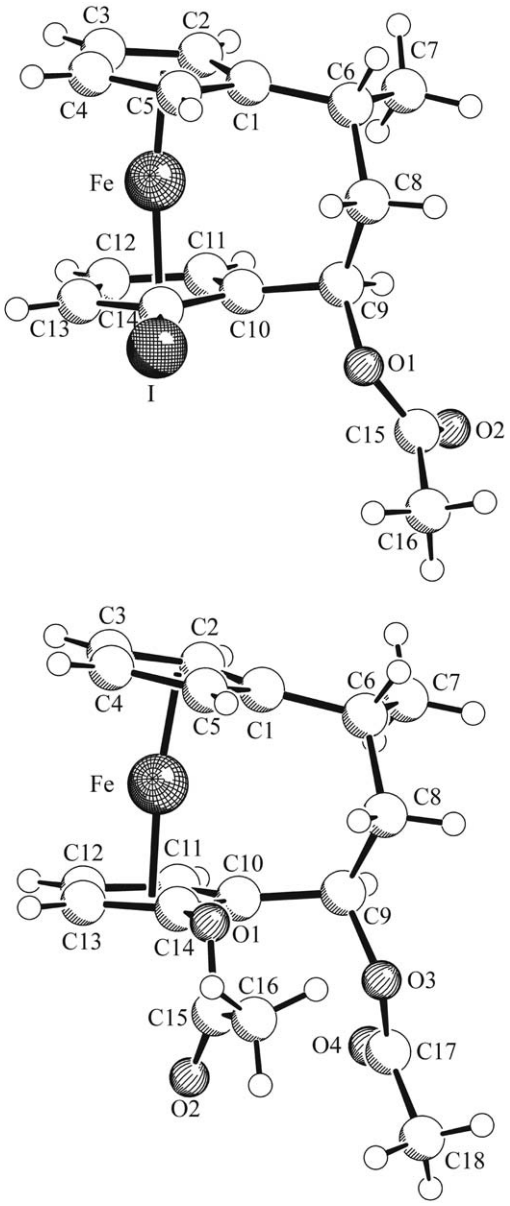
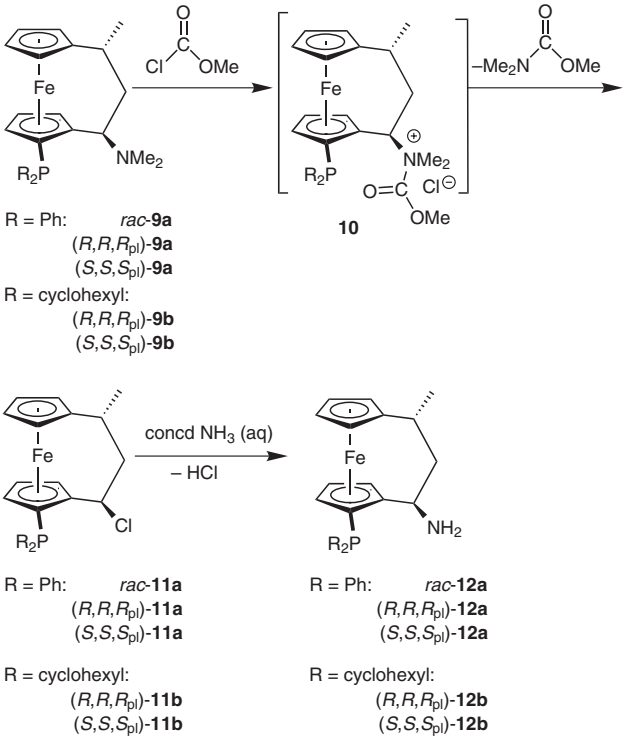



**Figure 2** Views of the molecular structures of the acetoxy-functionalized [3]ferrocenophane systems *rac*-**7** (top) and *rac*-**8** (bottom). Selected bond lengths (Å) and angles (°): **7**: C14–I 2.076(3), C9–O1 1.455(3), O1–C15 1.293(3), C15–O2 1.158(4), C10–C9–O1 107.9(2), C9–O1–C15 120.8(2); **8**: C14–O1 1.408(2), O1–C15 1.365(3), C15–O2 1.194(3), C9–O3 1.462(2), O3–C17 1.349(3), C17–O4 1.195(3), C14–O1–C15 115.6(2), C9–O3–C17 116.4(1).

lowing two-step sequence eventually turned out to be a practical solution to this problem. The complexes **9** were first converted to the α-chlorides by treatment with methylchloroformate (Scheme 3).[14] This route is probably initiated by amine attack on the reactive carbonic ester chloride (to generate **10**). This then undergoes the typical replacement of the in situ formed leaving group by anchimeric assistance of the iron center to eventually lead to **11** formed with overall retention of stereochemistry in a typical two-step double-inversion process.[11,12] In the diphenyl phosphine series the intermediate **11a** was isolated as




**Scheme 3**

the racemate and the pure enantiomers [i.e. ($R$,$R$,$R_{pl}$)-**11a** and ($S$,$S$,$S_{pl}$)-**11a**].

Stereoselective exchange of Cl by $NH_2$ was effected by treatment of the complexes **11a** with concentrated aqueous ammonia solution at 110 °C. This led to the clean formation of the α-amino-substituted diphenylphosphino [3]ferrocenophanes **12a** in ca. 50% yield.

The same route was carried out starting from the dicyclohexylphosphino[3]ferrocenophane dimethylamino derivatives ($R$,$R$,$R_{pl}$)-**9b** and ($S$,$S$,$S_{pl}$)-**9b**. In these cases the chloro derivatives **11b** were generated in situ by treatment with the methylchloroformate reagent and then directly subjected to the ammonolysis reaction to give ($R$,$R$,$R_{pl}$)-**12b** and ($S$,$S$,$S_{pl}$)-**12b**, in 26% yields, respectively (Figure 3).

The $^1$H NMR spectral features of the C6($CH_3$)–C8$H_2$–C9H($NH_2$) bridge of complex **12a** are very similar to

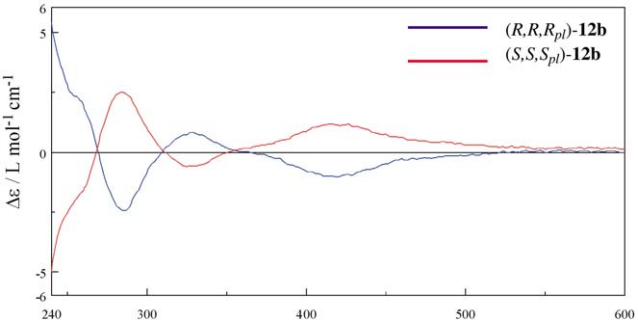


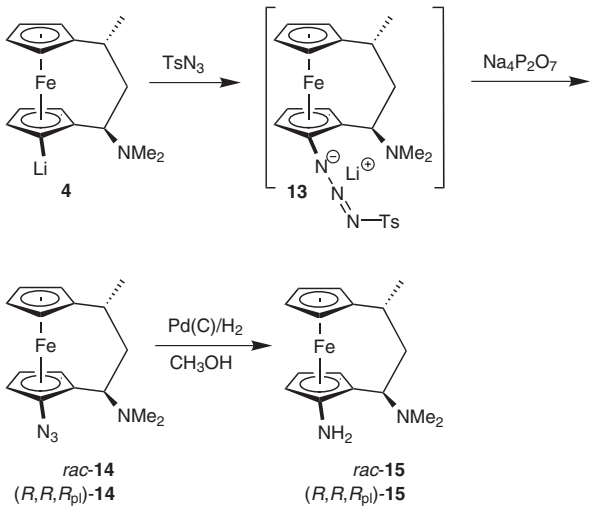

**Figure 3** CD-spectra of the pair of enantiomers ($R$,$R$,$R_{pl}$)-**12b** and ($S$,$S$,$S_{pl}$)-**12b**.

those of the dimethylamino derivative **9a** [δ(**12a**)/δ(**9a**) 2.72/2.85 (6-H), 3.06/3.17 (8-$H_a$), 2.13/2.30 (8-$H_b$), and 3.69/2.67 (9-H) ppm], so that we can assume these compounds have similar conformational structures in solution; they were found to have analogous conformations in the solid state. The X-ray crystal structure analyses of both the (*R*,*R*,$R_{pl}$)-**12a** and (*S*,*S*,$S_{pl}$)-**12a** enantiomers (Figure 4) show the presence of the typical chair-like bridge conformation at which the methyl substituent at C6 adopts a pseudo-axial position and the amino substituent at C9 is found oriented pseudo-equatorially. This consequently brings the C9–$NH_2$ and the C14–P1 vectors in a close to gauche arrangement relative to each other. The bulky phenyl substituents at the phosphorus atom in **12a** are both oriented away from the nitrogen substituent so that a large niche is created between the diphenylphosphino and amino substituents of the chiral chelate [3]ferrocenophane framework that seems to almost invite suitable metal complex fragments for chelate coordination.

We have also attached an amino substituent at the proximal position of the lower ferrocene Cp ring. Initially, this proved difficult since attempts by Buchwald–Hartwig amination[15] or Curtius or Hofmann degradation routes[16] were not successful.

Eventually the amino substituent could successfully be introduced via a Cp-bound azide (Scheme 4). This route was carried out for the racemic and the (*R*,*R*,$R_{pl}$)-enantiomeric series. Treatment of the dimethylamino[3]ferrocenophane **2** with *tert*-butyl lithium gave **4**, as described above (Scheme 2). The lithio[3]ferrocenophane **4** was then reacted with tosyl azide followed by pyrophosphate[17a,b] to yield the azido[3]ferrocenophane derivative **14**. Compound **14** shows the typical $^1$H NMR spectral pattern of the $C_3$-bridge hydrogen atoms at 2.18/2.78 (8-$H_a$/$H_b$), 2.83 (6-H), and 2.97 (9-H) ppm.

Single crystals were obtained from the *ortho*-azido[3]ferrocenophane amine derivative *rac*-**14** that allowed its characterization by X-ray diffraction. It features the typical 'chair-like' folded conformation of the $C_3$-bridge with the methyl substituent at C6 oriented in a pseudo-axial position and the dimethylamino substituent at C9 oriented pseudo-equatorially. The $N_3$ substituent at the adjacent ferrocene *ortho*-position is almost linear and arranged coplanar with the mean ferrocene Cp plane. The $N_3$ vector is oriented away from the substituted [3]ferrocenophane $C_3$-bridge (Figure 5).




**Scheme 4**

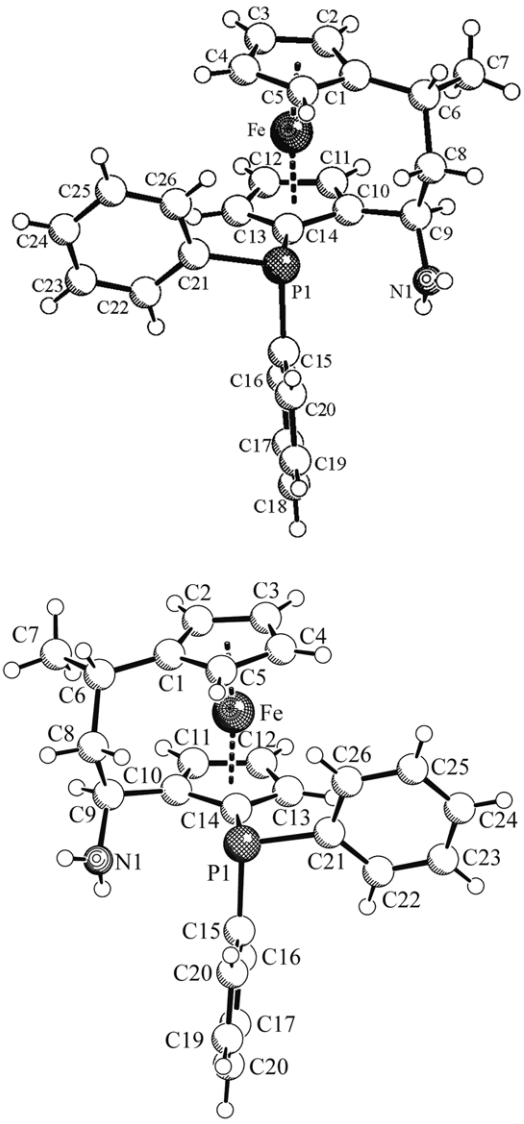



**Figure 4** Views of the structures of the separately synthesized enantiomers (*R*,*R*,$R_{pl}$)-**12a** (top) and (*S*,*S*,$S_{pl}$)-**12a** (bottom). Selected bond lengths (Å) and angles (°) of the *R* enantiomer: C14–P1 1.821(2), C9–N1 1.469(4), C14–P1–C21 100.2(1), C14–P1–C15 101.8(2), C21–P1–C15 101.1(1), C10–C9–N1 110.8(3), C8–C9–N1 107.1(3).

Reduction of the azido group in **14** was achieved by hydrogenolysis ($H_2$, Pd/C) in methanol.[17c] The (*R*,*R*,$R_{pl}$) enantiomer of the amino[3]ferrocenophane system **15** was obtained in >90% yield from this last step of the synthetic sequence. It features the amino IR bands at 3417 and 3325 $cm^{-1}$ and the typical $^1$H NMR spectral pattern of the bridge hydrogens at 2.33/2.45 (8-$H_a$/$H_b$), 2.67 (9-H), and 2.76 (6-H) ppm.

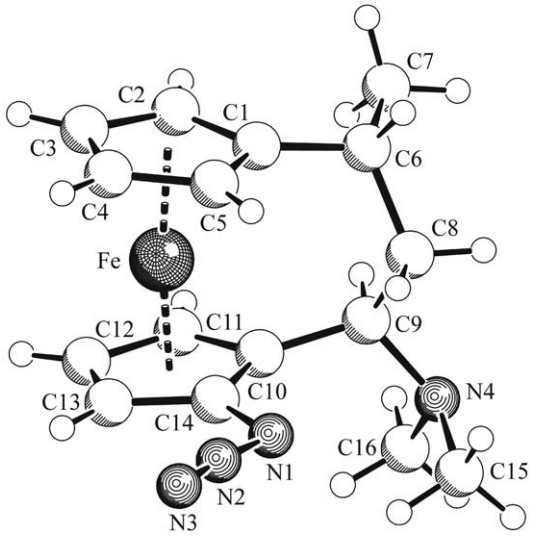
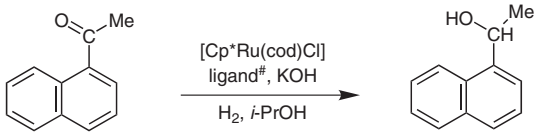



**Figure 5** Molecular structure of *rac*-**14** in the crystal. Selected bond lengths (Å) and angles (°): N2–N3 1.131(2), C10–C9 1.518(2), C9–N4 1.477(2), C14–N1–N2 114.1(1), N1–N2–N3 173.6(2), C10–C9–N4 116.2(1), C9–N4–C15 115.1(1), C9–N4–C16 111.4(1), C16–N4–C15 110.3(1).

## Ruthenium-Catalyzed Reactions

In some preliminary orientating experiments some of the ligands were briefly tested in asymmetric hydrogenation catalysis. In a typical series of experiments the chelate ligands ($R,R,R_{pl}$)-**12a** and ($S,S,S_{pl}$)-**12a** were each treated with [Cp*Ru(cod)Cl][18] using a protocol similar to that described by Ikariya et al.[19] The in situ generated Ru catalyst system effects the hydrogenation of a variety of ketones under ambient conditions with moderate yields and enantioselectivities (Table 1). The best result was obtained in the hydrogenation of 1-acetylnaphthalene which occurred in 94% yield and 83% ee. It should be noted that the [Ru]/($R,R,R_{pl}$)-**12a** systems effected the hydrogenation of the aliphatic ketone 2-hexanone in 52% yield and about 34% ee. The ligands ($R,R,R_{pl}$)-**12b** and ($R,R,R_{pl}$)-**15** were close to unreactive catalysts under these conditions.




ligand#: ($R,R,R_{pl}$)-**12a**, ($S,S,S_{pl}$)-**12a**, ($R,R,R_{pl}$)-**12b**

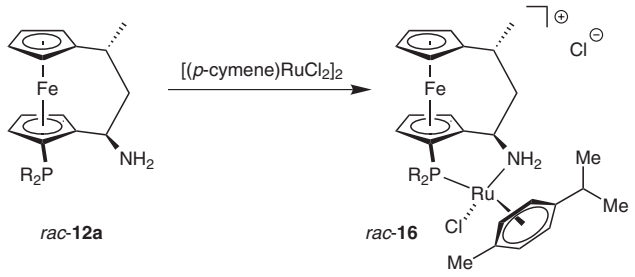
**Scheme 5**

Additionally, we briefly tested the new chelate ligands in Ru-catalyzed transfer hydrogenation[20] also using the substrates listed in Table 1. The catalysts generated in situ from the ligands ($R,R,R_{pl}$)-**12a**, ($R,R,R_{pl}$)-**12b**, and ($R,R,R_{pl}$)-**15** and [(*p*-cymene)$RuCl_2]_2$[21] actively catalyzed the hydrogen transfer from excess isopropanol but gave only moderate to low enantioselectivities.

**Table 1** Asymmetric Hydrogenation of Ketones with in situ Generated Chelate [3]Ferrocenophane Ligand/[Cp*Ru] Catalysts[a]


| $R^1$ | $R^2$ | Ligand | Time (h) | Yield (h) | ee (%) | Configuration |
|---|---|---|---|---|---|---|
| Ph | Me | ($R,R,R_{pl}$)-**12a** | 2 | 84 | 15 | *S* |
| Ph | Et | ($R,R,R_{pl}$)-**12a** | 2 | 99 | 49 | *S* |
| 1-Naphthyl | Me | ($R,R,R_{pl}$)-**12a** | 3 | 94 | 83 | *S* |
| 1-Naphthyl | Me | ($S,S,S_{pl}$)-**12a** | 3 | 94 | 80 | *R* |
| 2-Naphthyl | Me | ($R,R,R_{pl}$)-**12a** | 3 | 85 | 23 | *S* |
| Bu | Me | ($R,R,R_{pl}$)-**12a** | 3 | 52 | 34 | [b] |
| 1-Naphthyl | Me | ($R,R,R_{pl}$)-**12b** | 44 | 6 | 76 | *S* |

[a] Conditions: *i*-PrOH, r.t., $H_2$ (2 bar).
[b] Not determined.




**Scheme 6**

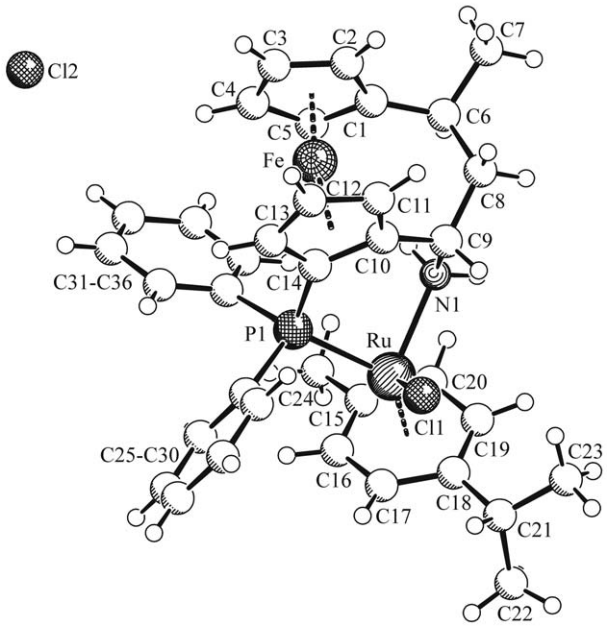



**Figure 6** Molecular structure of the ruthenium complex **16**. Selected bond lengths (Å) and angles (°): P1–Ru 2.323(1), Ru–Cl1 2.396(1), Ru–N1 2.174(4), Ru–C(15) to C(20) 2.181(5) to 2.288(5), P1–Ru–N1 86.4(1), P1–Ru–Cl1 83.8(1), N1–Ru–Cl1 88.1(1), C9–N1–Ru 122.1(3).

From one of a series of control experiments, in which *rac*-**12a** was treated with $[(p\text{-cymene})RuCl_2]_2$, we obtained single crystals of complex **16** (Scheme 6), which were characterized by X-ray diffraction.[22] In the crystal there is a single diastereoisomer (Figure 6) that features an *anti*-orientation of the [Ru]–Cl vector and the ferrocene core. The structure shows *quasi*-octahedral coordination at the central ruthenium atom with the $\eta^6$-cymene ligand formally occupying three coordination sites. The *P*,*N*-[3]ferrocenophane chelate and the remaining chloride ligand are found coordinated to the available octahedral face of the cationic complex. We assume that base-induced HCl elimination from this structure followed by hydrogen transfer generates the active species in transfer hydrogenation catalyses.[20]

In this study we have investigated ways to selectively attach simple oxygen and nitrogen substituents in a straightforward manner at the α-position of the bridge and the adjacent *ortho*-position at the Cp ring of the chiral [3]ferrocenophane framework. Not all of the attached groups themselves will be of value directly, but their underlying OH and $NH_2$ functionalities will probably allow for easy and valuable variations of the chelate functionalities. Since these systems are readily available in each of the enantiomerically pure forms we are hopeful that new [3]ferrocenophane chelate ligands derived from these relay complexes will become useful building blocks for future developments in selective homogeneous catalysis.

Reactions with air- and moisture-sensitive compounds were carried out in an inert atmosphere (argon) using Schlenk-type glassware or a glove box. Solvents were dried and distilled under argon prior to use. The following instruments were used for characterization: mp, TA instruments differential scanning calorimeter 2010; optical rotation, Perkin-Elmer 351 Polarimeter (25 °C, l = 589 nm, 1 dm cuvette, *c* 10 mg mL$^{-1}$); NMR spectroscopy: Bruker AC-200P-FT ($^1$H: 200.1 MHz, $^{13}$C: 50.3 MHz, $^{31}$P: 81.0 MHz), ARX 300 ($^1$H: 300.1 MHz, $^{13}$C: 75.5 MHz, $^{31}$P: 121.5 MHz), AMX 400 ($^1$H: 400.1 MHz, $^{13}$C: 100.6 MHz), Varian INOVA 500 ($^1$H: 499.8 MHz, $^{13}$C: 125.7 MHz), and UNITY Plus 600 ($^1$H: 599.1 MHz, $^{13}$C: 150.7 MHz); IR: Varian 3100 FT-IR Excalibur Series; UV-Vis: Varian Cary I Bio; CD: JASCO J-600 (*c* in mol/L); and elemental analyses: Foss-Heraeus CHN-O-Rapid. Compounds *rac*-**2**, (*R*,*R*)-**2**, (*S*,*S*)-**2**, *rac*-**9a**, (*R*,*R*,$R_{pl}$)-**9a**, (*S*,*S*,$S_{pl}$)-**9a**, (*R*,*R*,$R_{pl}$)-**9b**, and (*S*,*S*,$S_{pl}$)-**9b** were prepared as previously described by us.[3,6,9,10]

Data sets for the X-ray crystal structure analyses were collected on a Nonius Kappa CCD diffractometer, equipped with a rotating anode generator. Programs used: data collection, COLLECT;[23a] data reduction, Denzo-SMN;[23b] absorption correction, SORTAV[23c,23d] and Denzo;[23e] structure solution, SHELXS-97;[23f] structure refinement, SHELXL-97;[23g] and graphics, SCHAKAL.[23h]

### *rac*-5

To a solution of the tertiary amino[3]ferrocenophane *rac*-**2** (7.82 g, 27.6 mmol) in $Et_2O$ (250 mL), *t*-BuLi (1.5 M, hexane; 27.6 mL, 41.4 mmol) was added at 0 °C. After stirring for 30 min at r.t., the solution was cooled to 0 °C and $I_2$ (14.0 g, 55.2 mmol) was added. The reaction was stirred at r.t. for 2 h and then quenched with a sat. solution of $Na_2S_2O_3$ (150 mL). After phase separation the aqueous phase was extracted with $Et_2O$ (2 × 60 mL) and dried over $MgSO_4$. The crude product was purified via column chromatography ($SiO_2$, MeOH) to furnish 5.74 g (14.0 mmol, 51%) of an orange solid; $R_f$ = 0.37. Single crystals suitable for X-ray diffraction were grown from a sat. solution of $Et_2O$ or $CH_2Cl_2$.

$^1$H NMR (599.9 MHz, $CD_2Cl_2$): δ = 4.36 (m, 1 H, H-13), 4.31 (m, 1 H, H-4), 4.15 (m, 1 H, H-2), 4.11 (m, 1 H, H-12), 3.98 (m, 1 H, H-3), 3.96 (m, 1 H, H-11), 3.58 (m, 1 H, H-5), 2.84 (m, 2 H, 6-H, $H_{ax}$-8), 2.79 (dd, *J* = 11.5, 1.9 Hz, 1 H, H-9), 2.25 (m, 1 H, $H_{eq}$-8), 2.21 (s, 6 H, H-15), 1.25 (d, *J* = 7.4 Hz, 3 H, H-7).

$^{13}$C{$^1$H} NMR (150.8 MHz, $CD_2Cl_2$): δ = 95.5 (C-1), 83.1 (C-10), 81.5 (C-5), 78.2 (C-13), 72.0, (C-11), 70.7 (C-4), 69.4 (C-12), 68.8 (C-2), 68.0 (C-3), 60.3 (C-9), 45.5 (C-15), 44.8 (C-8), 42.3 (C-14), 28.2 (C-6), 17.0 (C-7).

Anal. Calcd for $C_{16}H_{20}FeIN$: C, 46.97; H, 4.94; N, 3.42. Found: C, 46.93; H, 4.79; N, 3.45.

X-ray crystal structure analysis (CCDC 607481): formula $C_{16}H_{20}FeIN$, *M* = 409.08, orange crystal 0.35 × 0.30 × 0.20 mm, *a* = 10.557(1), *b* = 12.531(1), *c* = 11.306(1) Å, β = 95.29(1)°, *V* = 1489.3(2) Å$^3$, $\rho_{calcd}$ = 1.824 gcm$^{-3}$, μ = 3.072 mm$^{-1}$, empirical absorption correction (0.413 ≤ *T* ≤ 0.579), *Z* = 4, monoclinic, space group $P2_1/c$ (No. 14), λ = 0.71073 Å, *T* = 198 K, ω and φ scans, 11588 reflections collected (±*h*, ±*k*, ±*l*), [(sinθ)/λ] = 0.67 Å$^{-1}$, 3616 independent ($R_{int}$ = 0.030) and 3335 observed reflections [$I \geq 2\sigma(I)$], 175 refined parameters, *R*1 = 0.024, *wR*2 = 0.058, max. residual electron density 0.44 (–0.81) eÅ$^{-3}$, hydrogens are calculated and all refined as riding atoms.

### *rac*-7

Compound *rac*-**5** (1.17 g, 2.86 mmol) and $Cu_2O$ (0.41 g, 2.86 mmol) were suspended in MeCN (40 mL), then $Ac_2O$ was added (0.7 mL, 7.15 mmol) and the mixture was refluxed for 6 h. After filtration the crude product was purified via column chromatography ($SiO_2$, cyclohexane–EtOAc, 3:1) to furnish 0.60 g (1.40 mmol, 49%) of a yellow powder along with a second product *rac*-**2** (87 mg, 0.24 mmol, 8%); $R_f$ = 0.81. Single crystals suitable for X-ray diffraction were grown from a solution of $CD_2Cl_2$. The compound was only characterized by X-ray diffraction and elemental analysis.

Anal. Calcd for $C_{16}H_{17}FeIO_2$: C, 45.32; H, 4.04. Found: C, 45.43; H, 3.92.

X-ray crystal structure analysis (CCDC 607479): formula $C_{16}H_{17}FeIO_2$, *M* = 424.05, orange crystal 0.35 × 0.30 × 0.30 mm, *a* = 6.915(1), *b* = 7.433(1), *c* = 14.706(1) Å, α = 80.70(1)°, β = 85.82(1)°, γ = 88.86(1)°, *V* = 743.9(2) Å$^3$, $\rho_{calcd}$ = 1.893 g cm$^{-3}$, μ = 3.086 mm$^{-1}$, empirical absorption correction (0.411 ≤ *T* ≤ 0.458), *Z* = 2, triclinic, space group *P*–1 (No. 2), λ = 0.71073 Å, *T* = 198 K, ω and φ scans, 7526 reflections collected (±*h*, ±*k*, ±*l*), [(sinθ)/λ] = 0.67 Å$^{-1}$, 3583 independent ($R_{int}$ = 0.040) and 3293 observed reflections [$I \geq 2\sigma(I)$], 183 refined parameters, *R*1 = 0.028, *wR*2 = 0.080, max. residual electron density 0.69 (–1.19) eÅ$^{-3}$, hydrogens are calculated and all refined as riding atoms.

### *rac*-8

To a solution of *rac*-**5** (6.06 g, 14.8 mmol) in MeCN (60 mL), $Ac_2O$ (8.0 mL, 84.8 mmol) and $Cu_2O$ (2.12 g, 14.8 mmol) were added and the mixture was refluxed for 16 h. The solvent was removed under reduced pressure and the residue was extracted with EtOAc. The crude product was purified by column chromatography ($SiO_2$, cyclohexane–EtOAc, 3:1) to furnish 5.15 g (14.5 mmol) of a yellow solid; $R_f$ = 0.63. Single crystals suitable for X-ray diffraction were grown from a solution of $CD_2Cl_2$.

$^1$H NMR (599.9 MHz, $CD_2Cl_2$): δ = 5.51 (dd, *J* = 10.7, 3.4 Hz, 1 H, H-9), 4.30 (m, 1 H, H-5), 4.25 (m, 1 H, H-13), 4.24 (m, 1 H, H-2), 4.04 (m, 1 H, H-4), 4.02 (m, 1 H, H-3), 4.00 (m, 1 H, H-11), 3.90 (m, 1 H, H-12), 2.80 (m, 2 H, 6-H, $H_{ax}$-8), 2.19 (s, 3 H, H-18), 2.13 (m, 1 H, $H_{eq}$-8), 1.93 (s, 3 H, H-16), 1.30 (d, *J* = 7.3 Hz, 3 H, H-7).

$^{13}C\{^1H\}$ NMR (150.8 MHz, $CD_2Cl_2$): δ = 170.7 (C-15, C-17), 115.9 (C-14), 94.2 (C-1), 73.4 (C-4), 73.3 (C-10), 71.0 (C-5), 68.9 (C-2), 68.1 (C-3), 67.9 (C-9), 65.8 (C-11), 64.4 (C-13), 63.7 (C-12), 47.0 (C-8), 27.7 (C-6), 21.2 (C-18), 21.1 (C-16), 17.4 (C-7).

Anal. Calcd for $C_{18}H_{20}FeO_4$: C, 60.70; H, 5.66. Found: C, 60.33; H, 5.53.

X-ray crystal structure analysis (CCDC 607480): formula $C_{18}H_{20}FeO_4$, $M$ = 356.19, yellow crystal 0.55 × 0.55 × 0.20 mm, $a$ = 15.768(1), $b$ = 7.125(1), $c$ = 16.315(1) Å, $\beta$ = 118.56(1)°, $V$ = 1609.9(3) Å$^3$, $\rho_{calcd}$ = 1.470 gcm$^{-3}$, μ = 0.954 mm$^{-1}$, empirical absorption correction ($0.702 \le T \le 0.972$), $Z$ = 4, monoclinic, space group $P2_1/n$ (No. 14), λ = 0.71073 Å, $T$ = 198 K, ω and φ scans, 10776 reflections collected (±$h$, ±$k$, ±$l$), [(sinθ)/λ] = 0.66 Å$^{-1}$, 3837 independent ($R_{int}$ = 0.053) and 2769 observed reflections [$I \ge 2\sigma(I)$], 211 refined parameters, $R1$ = 0.038, $wR2$ = 0.096, max. residual electron density 0.32 (–0.40) eÅ$^{-3}$, hydrogens are calculated and all refined as riding atoms.

**Compound 11a**

***rac*-11a**

$NaHCO_3$ (5.92 g, 70.6 mmol) was added to a solution of *rac*-**9a** (4.12 g 8.82 mmol) in toluene (40 mL) and stirred for 30 min. Methylchloroformate (4.10 mL, 52.9 mmol) was added and the mixture was stirred for 2 h. The suspension was filtered through celite, the solvent was removed under reduced pressure, and the crude product was dried for 16 h to remove high boiling by-products to furnish 3.96 g (8.64 mmol, 98%) of *rac*-**11a**. Single crystals suitable for X-ray diffraction were grown from a solution of toluene at –32 °C.

$^1H$ NMR (599.9 MHz, $CD_2Cl_2$): δ = 7.51–7.47 (m, 2 H, *o*-Ph), 7.38–7.35 (m, 3 H, *m*-Ph, *p*-Ph), 7.27–7.24 (m, 3 H, *m*-Ph, *p*-Ph), 7.24–7.20 (m, 2 H, *o*-Ph), 4.84 (dd, $J$ = 12.5, 3.1 Hz, 1 H, H-9), 4.56 (m, 1 H, H-5), 4.36 (m, 1 H, H-11), 4.25 (m, 1 H, H-12), 4.22 (m, 1 H, H-2), 3.86 (m, 1 H, $H_{ax}$-8), 3.84 (m, 1 H, H-3), 3.69 (m, 1 H, H-13), 3.60 (m, 1 H, H-4), 2.84 (m, 1 H, H-6), 2.44 (m, 1 H, $H_{eq}$-8), 1.28 (d, $J$ = 7.3 Hz, 3 H, H-7).

$^{13}C\{^1H\}$ NMR (150.8 MHz, $CD_2Cl_2$): δ = 140.2 (d, $J_{P,C}$ = 9.3 Hz, *i*-Ph), 138.3 (d, $J_{P,C}$ = 10.7 Hz, *i*-Ph), 135.3 (d, $J_{P,C}$ = 20.8 Hz, *o*-Ph), 133.1 (d, $J_{P,C}$ = 18.3 Hz, *o*-Ph), 129.3 (*p*-Ph), 128.3 (d, $J_{P,C}$ = 7.3 Hz, *m*-Ph), 128.1 (*p*-Ph), 128.1 (d, $J_{P,C}$ = 7.3 Hz, *m*-Ph), 93.3 (C-1), 87.5 (d, $J_{P,C}$ = 18.9 Hz, C-10), 76.0 (d, $J_{P,C}$ = 16.0 Hz, C-14), 75.2 (d, $J_{P,C}$ = 4.6 Hz, C-13), 73.7 (d, $J_{P,C}$ = 4.1 Hz, C-11), 72.8 (d, $J_{P,C}$ = 5.8 Hz, C-5), 70.8 (C-4), 70.4 (C-12), 69.4 (C-2), 68.1 (C-3), 56.2 (C-9), 52.4 (d, $J_{P,C}$ = 10.5 Hz, C-8), 29.3 (C-6), 16.4 (C-7).

$^{31}P\{^1H\}$ NMR (81.0 MHz, $CD_2Cl_2$): δ = –21.6.

MS (EI, 70 eV): $m/z$ (%) = 458 (100) [M$^+$], 422 (65) [(M – Cl)$^+$], 275 (77).

**($R$,$R$,$R_{pl}$)-11a**

According to the procedure described above $NaHCO_3$ (1.82 g, 21.6 mmol, 8.0 equiv) was added to a solution of ($R$,$R$,$R_{pl}$)-**9a** (1.26 g, 2.70 mmol, 1 equiv) in toluene (14.5 mL) followed by methylchloroformate (1.30 mL, 1.59 g, 16.8 mmol, 6.2 equiv) to furnish 1.23 g (99%) of ($R$,$R$,$R_{pl}$)-**11a**.

**($S$,$S$,$S_{pl}$)-11a**

According to the procedure described above $NaHCO_3$ (1.67 g, 19.9 mmol, 8.0 equiv) was added to a solution of ($S$,$S$,$S_{pl}$)-**9a** (1.16 g, 2.48 mmol, 1.0 equiv) in toluene (12.5 mL) followed by methylchloroformate (1.15 mL, 1.40 g, 14.8 mmol, 6.0 equiv) to furnish 1.14 g (quantitative) of ($S$,$S$,$S_{pl}$)-**11a**.

**Compound 12a**

***rac*-12a**

A sample of *rac*-**11a** (1.27 g, 2.76 mmol) was dissolved in toluene (9.2 mL) and placed in a Schlenk tube fitted with a Teflon screw cap. An aq concd solution of $NH_3$ (4.6 mL) was added and the sealed flask was heated behind a safety shield for 5 h at 110 °C. The mixture was cooled to r.t. and then a solution of $NaHCO_3$ (10 mL) was added. The organic phase was separated, a 1 M solution of NaOH (10 mL) was added to the aqueous phase which was then extracted with $CH_2Cl_2$ (3 × 10 mL). The combined organic phases were washed with a solution of 1 M NaOH (10 mL), a solution of $NaHCO_3$ (10 mL), and then dried over $MgSO_4$. The solvent was removed in vacuo and the product purified by column chromatography (silica gel, MeOH) to furnish a yellow solid (700 mg, 58%); $R_f$ = 0.53.

**($R$,$R$,$R_{pl}$)-12a**

According to the procedure described above ammonolysis of ($R$,$R$,$R_{pl}$)-**9a** (1.09 g, 2.37 mmol) in toluene (8 mL) with a concd aq solution of $NH_3$ (4 mL) furnished 553 mg (53%) of ($R$,$R$,$R_{pl}$)-**12a**; $[\alpha]_D^{20}$ +258 ($c$ 1.1 × 10$^{-1}$, MeCN). Single crystals were obtained from MeOH at –20 °C.

Anal. Calcd for $C_{26}H_{26}NPFe \cdot 0.85H_2O$: C, 68.68; H, 6.15; N, 3.08. Found: C, 69.17; H, 5.76; N, 2.88; $H_2O$ present in the sample according to NMR spectroscopy.

X-ray crystal structure analysis (CCDC 607477): formula $C_{26}H_{26}NPFe$, $M$ = 439.30, orange crystal 0.30 × 0.15 × 0.10 mm, $a$ = 8.929(1), $b$ = 14.965(1), $c$ = 15.778(1) Å, $V$ = 2108.3(3) Å$^3$, $\rho_{calcd}$ = 1.384 gcm$^{-3}$, μ = 0.803 mm$^{-1}$, empirical absorption correction ($0.795 \le T \le 0.924$), $Z$ = 4, orthorhombic, space group $P2_12_12_1$ (No. 19), λ = 0.71073 Å, $T$ = 293 K, ω and φ scans, 12682 reflections collected (±$h$, ±$k$, ±$l$), [(sinθ)/λ] = 0.66 Å$^{-1}$, 5030 independent ($R_{int}$ = 0.048) and 3486 observed reflections [$I \ge 2\sigma(I)$], 271 refined parameters, $R1$ = 0.040, $wR2$ = 0.073, Flack parameter 0.01(1), max. residual electron density 0.24 (–0.29) eÅ$^{-3}$, hydrogen atoms at N1 from difference Fourier map, others are calculated and refined as riding atoms.

**($S$,$S$,$S_{pl}$)-12a**

According to the procedure described above ammonolysis of ($S$,$S$,$S_{pl}$)-**9a** (1.01 g, 2.21 mmol) in toluene (7.4 mL) with a concd aq solution of $NH_3$ (3.7 mL) furnished 497 mg (51%) of ($S$,$S$,$S_{pl}$)-**12a**; mp 185.2 °C; $[\alpha]_D^{20}$ –253 ($c$ 1.1 × 10$^{-1}$, MeCN).

IR (ATR): 3049, 2963, 2916, 2860, 1434, 1027 cm$^{-1}$.

$^1H$ NMR (599.9 MHz, $CD_2Cl_2$): δ = 7.23–7.45 (m, 10 H, Ph), 4.42 (m, 1 H, H-5), 4.27 (m, 1 H, H-11), 4.15 (m, 1 H, H-12), 4.14 (m, 1 H, H-2), 3.85 (m, 1 H, H-3), 3.69 (m, 1 H, H-9), 3.66 (m, 1 H, H-4), 3.48 (m, 1 H, H-13), 3.06 (m, 1 H, $H_a$-8), 2.72 (m, 1 H, H-6), 2.13 (ddd, $^2J$ = 13.4 Hz, $^3J$ = 5.0 Hz, $^3J$ = 3.4 Hz, 1 H, $H_b$-8), 1.61 (br, 2 H, H-15), 1.26 (d, $^3J$ = 7.2 Hz, 3 H, H-7).

$^{13}C\{^1H\}$ NMR (150.8 MHz, $CD_2Cl_2$): δ = 140.5 (d, $J_{P,C}$ = 10.2 Hz, *i*-Ph), 138.1 (d, $J_{P,C}$ = 11.0 Hz, *i*-Ph), 134.0 (d, $J_{P,C}$ = 20.2 Hz, Ph), 132.9 (d, $J_{P,C}$ = 18.4 Hz, Ph), 129.2 (Ph), 128.5 (d, $J_{P,C}$ = 5.6 Hz, Ph), 128.4 (d, $J_{P,C}$ = 7.6 Hz, Ph), 128.3 (Ph), 93.9 (C-1), 93.0 (d, $J_{P,C}$ = 18.0 Hz, C-10), 74.5 (d, $J_{P,C}$ = 11.1 Hz, C-14), 73.9 (d, $J_{P,C}$ = 4.2 Hz, C-11), 73.8 (br, C-13), 73.0 (d, $J_{P,C}$ = 6.0 Hz, C-5), 69.8 (C-2), 69.8 (C-4), 68.7 (C-2), 67.9 (C-3), 51.7 (d, $J_{P,C}$ = 6.8 Hz, C-8), 45.8 (C-9), 27.4 (C-6), 17.7 (C-7).

$^{31}P\{^1H\}$ NMR (81.0 MHz, $CD_2Cl_2$): δ = –19.5.

MS (ESI, ES$^+$, MeCN): $m/z$ = 440.2 [(M + H)$^+$].

UV/Vis ($CH_2Cl_2$): $\lambda_{max}$ (ε) = 435 (120), 258 (11300), 228 (12000).

Anal. Calcd for $C_{26}H_{26}NPFe \cdot 0.41H_2O$: C, 69.90; H, 6.06; N, 3.14. Found: C, 69.34; H, 5.77; N, 2.96.

X-ray crystal structure analysis (CCDC 607476): formula $C_{26}H_{26}NPFe$, $M = 439.30$, yellow crystal $0.30 \times 0.30 \times 0.15$ mm, $a = 8.896(1)$, $b = 14.893(1)$, $c = 15.673(1)$ Å, $V = 2076.5(3)$ Å$^3$, $\rho_{calcd} = 1.405$ gcm$^{-3}$, $\mu = 0.816$ mm$^{-1}$, empirical absorption correction ($0.792 \le T \le 0.887$), $Z = 4$, orthorhombic, space group $P2_12_12_1$ (No. 19), $\lambda = 0.71073$ Å, $T = 198$ K, ω and φ scans, 13544 reflections collected ($\pm h$, $\pm k$, $\pm l$), $[(\sin\theta)/\lambda] = 0.67$ Å$^{-1}$, 4880 independent ($R_{int} = 0.036$) and 4575 observed reflections [$I \ge 2\sigma(I)$], 271 refined parameters, $R1 = 0.026$, $wR2 = 0.059$, Flack parameter –0.01(1), max. residual electron density 0.23 (–0.24) eÅ$^{-3}$, hydrogen atoms at N1 from difference Fourier map, others are calculated and refined as riding atoms.

### Compound 12b

#### (*R*,*R*,*R*$_{pl}$)-12b

A sample of (*R*,*R*,*R*$_{pl}$)-**9b** (814 mg, 1.74 mmol) in toluene (8.7 mL) was charged with $NaHCO_3$ (1.18 g, 13.9 mmol, 8 equiv) and the mixture was stirred for 45 min at r.t. Then methylchloroformate (0.81 mL, 0.99 g, 10.5 mmol, 6 equiv) was added via syringe. The mixture was stirred for 5 h, then filtered, and the volatiles removed in vacuo to give 781 mg of the crude product that apparently contained (*R*,*R*,*R*$_{pl}$)-**11b**. This material (715 mg) was dissolved in toluene (6 mL), a concd aq solution of $NH_3$ (3 mL) was added, and the mixture was heated for 5 h at 110 °C in a sealed (Teflon screw cap) Schlenk tube behind a safety shield. The mixture was cooled to r.t., a sat. solution of $NaHCO_3$ (5 mL) was added, and the organic phase separated. The aqueous phase was extracted with $CH_2Cl_2$ (3 × 10 mL). The combined organic solutions were washed with a solution of $NaHCO_3$ (10 mL), a solution of 1 M NaOH (10 mL), and then dried over $MgSO_4$. The solvent was removed in vacuo and the product was purified by column chromatography (silica gel, first MeOH then repeated chromatography with $Et_2O$ gave the pure product) to furnish 189 mg (26%) of (*R*,*R*,*R*$_{pl}$)-**12b**; $R_f = 0.33$ (MeOH); mp 108.7 °C; $[\alpha]_D^{20}$ +238 (*c* $1.0 \times 10^{-1}$, $CH_2Cl_2$).

CD (*c* $8.9 \times 10^{-5}$, $CH_2Cl_2$): Δε ($\lambda_{max}$) = –2.45 (285), +0.76 (328), –1.05 (418).

IR (ATR): 3091, 2920, 2849, 1444, 1261, 1079, 1039, 802 cm$^{-1}$.

$^1$H NMR (599.9 MHz, $CD_2Cl_2$): δ = 4.15 (m, 1 H, H-12 or H-13), 4.12 (m, 1 H, H-12 or H-13), 4.11 (m, 1 H, H-3 or H-4), 4.10 (m, 1 H, H-2 or H-3), 4.02 (m, 1 H, H-11), 3.97 (m, 1 H, H-3 or H-4), 3.95 (m, 1 H, H-2 or H-5), 3.60 (m, 1 H, H-9), 2.81 (m, 1 H, H′-8), 2.59 (m, 1 H, H-6), 2.34 [m, 1 H, (P)CH$_2$], 2.12 [m, 1 H, (P)CH], 2.04 [m, 1 H, H-8], 2.01 [m, 1 H, (P)CH$_2$], 1.87 [m, 1 H, (P)CH$_2$], 1.86 [(m, 1 H, (P)CH$_2$], 1.85 [m, 1 H, (P)CH$_2$], 1.77 [m, 1 H, (P)CH$_2$], 1.73 [m, 1 H, (P)CH$_2$], 1.69 [m, 1 H, (P)CH$_2$], 1.62 [m, 1 H, (P)CH$_2$], 1.61 [m, 1 H, (P)CH], 1.42 [m, 1 H, (P)CH$_2$], 1.38 [m, 1 H, (P)CH$_2$], 1.37 [m, 2 H, (P)CH$_2$], 1.36 [m, 1 H, (P)CH$_2$], 1.27 [m, 2 H, (P)CH$_2$], 1.27 (br, 2 H, H-15), 1.22 (d, *J* = 7.2 Hz, 3 H, H-7), 1.18 [m, 2 H, (P)CH$_2$], 1.10 [m, 1 H, (P)CH$_2$], 0.98 [m, 1 H, (P)CH$_2$].

$^{13}$C{$^1$H} NMR (150.8 MHz, $CD_2Cl_2$): δ = 94.2 (C-1), 93.3 (d, $J_{P,C}$ = 19.2 Hz, C-10), 78.1 (d, $J_{P,C}$ = 23.6 Hz, C-14), 72.3 (d, $J_{P,C}$ = 4.4 Hz, C-11), 72.2 (d, $J_{P,C}$ = 4.4 Hz, C-3 or C-4), 71.5 (C-2 or C-5), 69.9 (C-2 or C-5), 69.3 (C-12 or C-13), 68.3 (C-12 or C-13), 67.9 (C-3 or C-4), 53.2 (d, $J_{P,C}$ = 7.4 Hz, C-8), 46.6 (C-9), 37.1 [d, $J_{P,C}$ = 11.4 Hz, (P)CH], 36.4 [d, $J_{P,C}$ = 11.8 Hz, (P)CH], 34.4 [d, $J_{P,C}$ = 24.5 Hz, (P)CH$_2$], 31.7 [d, $J_{P,C}$ = 16.8 Hz, (P)CH$_2$], 31.5 [d, $J_{P,C}$ = 10.8 Hz, (P)CH$_2$], 30.4 [d, $J_{P,C}$ = 3.5 Hz, (P)CH$_2$], 30.1 [(P)CH$_2$], 28.5 [d, $J_{P,C}$ = 15.5 Hz, (P)CH$_2$], 28.1 [d, $J_{P,C}$ = 6.0 Hz, (P)CH$_2$], 28.0 [d, $J_{P,C}$ = 9.0 Hz, (P)CH$_2$], 27.6 [d, $J_{P,C}$ = 10.8 Hz, (P)CH$_2$], 27.2 (C-6), 26.9 [d, $J_{P,C}$ = 13.5 Hz, (P)CH$_2$], 17.8 (C-7).

$^{31}$P{$^1$H} NMR (81.0 MHz, $CD_2Cl_2$): δ = –13.0.

MS (ESI, ES$^+$, MeOH): *m*/*z* = 452.2 [(M + H)$^+$].

UV/Vis ($CH_2Cl_2$): $\lambda_{max}$ (ε) = 260 (10500), 228 (14800).

Anal. Calcd for $C_{26}H_{38}NPFe$: C, 69.17; H, 8.50; N, 3.10. Found: C, 68.57; H, 8.62; N, 2.79.

#### (*S*,*S*,*S*$_{pl}$)-12b

Prepared according to the procedure described above. (*S*,*S*,*S*$_{pl}$)-**9b** (469 mg, 0.98 mmol) and $NaHCO_3$ (658 mg, 7.8 mmol) in toluene (0.45 mL) were treated with methylchloroformate (0.55 g, 5.80 mmol) in toluene (4.9 mL) to furnish 443 mg of the crude intermediate. Ammonolysis of the crude (384 mg) with a concd solution of ammonia (3 mL) in toluene (4 mL) furnished 101 mg (26%) of (*S*,*S*,*S*$_{pl}$)-**12b** after chromatographic purification (first MeOH, then $Et_2O$); $[\alpha]_{589}^{20}$ –215 (*c* $1.0 \times 10^{-1}$, $CH_2Cl_2$).

CD (*c* $8.9 \times 10^{-5}$, $CH_2Cl_2$): Δε ($\lambda_{max}$) = +2.47 (285), –0.64 (328), +1.11 (417).

Anal. Calcd for $C_{26}H_{38}NPFe$: C, 69.17; H, 8.50; N, 3.10. Found: C, 68.76; H, 8.63; N, 2.84.

### Compound 14

#### *rac*-14

A sample of *rac*-**2** (433 mg, 1.53 mmol) in $Et_2O$ (3 mL) was treated with *t*-BuLi (1.5 M in pentane; 1.5 mL, 2.25 mmol, 1.5 equiv) at 0 °C. After stirring for 1 h at ambient temperature the mixture was cooled to –78 °C. A solution of *p*-tosyl azide (450 mg, 2.28 mmol, 1.5 equiv) in $Et_2O$ (3 mL) was added dropwise. The mixture was stirred at –78 °C for 5 h, warmed to 0 °C, stirred for 10 min, and then $Na_4P_2O_7{\cdot}10H_2O$ (736 mg, 1.65 mmol, 1.1 equiv) in $H_2O$ (7.5 mL) was added. After stirring overnight at r.t. the solvent was removed, the residue was taken up in $H_2O$ (5 mL), and extracted with $CH_2Cl_2$ (3 × 10 mL). The combined organic solutions were dried over $MgSO_4$ and the solvent was removed in vacuo. The product was purified by column chromatography (silica gel, MeOH). The product was then dissolved in $Et_2O$ and filtered. Removal of the solvent furnished 176 mg (36%) of pure *rac*-**14**; $R_f = 0.27$. Single crystals were obtained from a $Et_2O$ solution by slow evaporation of the solvent at –20 °C.

Anal. Calcd for $C_{16}H_{20}N_4Fe$: C, 59.25; H, 6.23; N, 17.28. Found: C, 59.69; H, 6.10; N, 16.87.

X-ray crystal structure analysis (CCDC 607475): formula $C_{16}H_{20}N_4Fe$, $M = 324.21$, yellow crystal $0.55 \times 0.55 \times 0.20$ mm, $a = 14.760(1)$, $b = 7.348(1)$, $c = 15.120(1)$ Å, $\beta = 113.48(1)°$, $V = 1504.1(2)$ Å$^3$, $\rho_{calcd} = 1.432$ g cm$^{-3}$, $\mu = 1.001$ mm$^{-1}$, empirical absorption correction ($0.609 \le T \le 0.825$), $Z = 4$, monoclinic, space group $P2_1/n$ (No. 14), $\lambda = 0.71073$ Å, $T = 198$ K, ω and φ scans, 9935 reflections collected ($\pm h$, $\pm k$, $\pm l$), $[(\sin\theta)/\lambda] = 0.66$ Å$^{-1}$, 3594 independent ($R_{int} = 0.025$) and 3333 observed reflections [$I \ge 2\sigma(I)$], 193 refined parameters, $R1 = 0.026$, $wR2 = 0.068$, max. residual electron density 0.35 (–0.35) eÅ$^{-3}$, hydrogens are calculated and all refined as riding atoms.

#### (*R*,*R*,*R*$_{pl}$)-14

According to the procedure described above, (*R*,*R*,*R*$_{pl}$)-**4** (445 mg, 1.57 mmol) was treated with *t*-BuLi (1.5 M, pentane; 1.60 mL, 2.40 mmol, 1.5 equiv), followed by tosyl azide (477 mg, 2.41 mmol, 1.5 equiv) in $Et_2O$ (3 mL) and $Na_4P_2O_7{\cdot}10H_2O$ (700 mg, 1.57 mmol, 1.0 equiv) in $H_2O$ (7.5 mL) to furnish 283 mg (55%) of (*R*,*R*,*R*$_{pl}$)-**14**; mp 113.7 °C (dec.); $[\alpha]_{589}^{20}$ +1120 (*c* $1.0 \times 10^{-1}$, $CH_2Cl_2$).

CD (*c* $3.2 \times 10^{-5}$, $CH_2Cl_2$): Δε ($\lambda_{max}$) = +17.05 (256), +21.76 (272), –0.65 (307),+1.18 (338), +0.22 (391), +2.86 (458).

IR (ATR): 2962, 2931, 2877, 2100, 1449, 1038, 801 cm$^{-1}$.

$^1$H NMR (599.9 MHz, $CD_2Cl_2$): δ = 4.40 (m, 1 H, $C_5H_4$), 4.34 (m, 1 H, $C_5H_3$), 4.17 (m, 1 H, $C_5H_4$), 4.00 (m, 1 H, $C_5H_4$), 3.96 (m, 1 H, $C_5H_3$), 3.93 (m, 1 H, $C_5H_4$), 3.92 (m, 1 H, $C_5H_3$), 2.97 (m, 1 H, H-9), 2.83 (m, 1 H, H-6), 2.78 (m, 1 H, H′-8), 2.23 (s, 6 H, H-15), 2.18 (m, 1 H, H-8), 1.25 (d, $^3J$ = 7.2 Hz, 3 H, H-7).

$^{13}C\{^1H\}$ NMR (150.8 MHz, $CD_2Cl_2$): δ = 98.1 (C-10), 95.0 (C-1), 75.6 (C-14), 73.2 ($C_5H_4$), 70.6 ($C_5H_4$), 70.5 ($C_5H_3$), 68.9 ($C_5H_4$), 66.9 ($C_5H_4$), 64.6 ($C_5H_3$), 61.6 ($C_5H_3$), 59.1 (C-9), 45.2 (C-8), 44.3 (C-15), 28.1 (C-6), 17.1 (C-7).

MS (EI, 70 eV): *m/z* (%) = 324.1 (40) [$M^+$], 296.0 (76) [$M^+ - N_2$], 253.0 (100), 160.9 (47), 147.9 (36), 121.9 (22).

UV/Vis ($CH_2Cl_2$): $\lambda_{max}$ (ε) = 274 (27100), 228 (17900).

Anal. Calcd for $C_{16}H_{20}N_4Fe$: C, 59.25; H, 6.23; N, 17.28. Found: C, 59.90; H, 6.14; N, 16.81.

**Compound 15**

***rac*-15**

A sample of *rac*-**14** (100 mg, 0.31 mmol) was dissolved in MeOH (3 mL). The solution was degassed by passing argon through it for 5 min. Then 10% Pd/C (12 mg) was added and the mixture was stirred for 2.5 h at a $H_2$ pressure of 1 bar. The mixture was filtered through Celite and the Celite washed with a small amount of $CH_2Cl_2$. The solvent was removed and the resulting yellow oil was kept under argon, to furnish 71 mg (77%) of *rac*-**15**.

IR (ATR): 3417, 3325, 3087, 2955, 2862, 2817, 2769, 2360, 2339, 1592, 1484, 1467, 1024, 790, 666 $cm^{-1}$.

$^1H$ NMR (499.8 MHz, $CD_2Cl_2$): δ = 4.23 (m, 1 H, H-3 or H-4), 3.94 (m, 1 H, H-2), 3.82 (m, 1 H, H-3 or H-4), 3.74 (m, 1 H, H-12 or H-13), 3.65 (m, 1 H, H-12 or H-13), 3.59 (m, 1 H, H-11), 3.43 (m, 1 H, H-5), 3.02 (br, 2 H, H-16), 2.76 (m, 1 H, H-6), 2.67 (dd, $^3J$ = 9.9 Hz, $^3J$ = 3.5 Hz, 1 H, H-9), 2.45 (m, 1 H, $H_b$-8), 2.33 (ddd, $^2J$ = 13.6 Hz, $^3J$ = 5.7 Hz, $^3J$ = 3.5 Hz, 1 H, $H_a$-8), 2.25 (s, 6 H, H-15), 1.25 (d, $^3J$ = 7.3 Hz, 3 H, H-7).

$^{13}C\{^1H\}$ NMR (125.7 MHz, $CD_2Cl_2$): δ = 106.9 (C-14), 93.1 (C-1), 77.0 (C-5), 75.2 (C-10), 69.8 (C-3 or C-4), 66.4 (C-2), 66.2 (C-3 or C-4), 65.8 (C-11), 61.9 (C-12 or C-13), 60.8 (C-9), 57.8 (C-12 or C-13), 45.8 (C-8), 45.4 (C-15), 27.2 (C-6), 18.4 (C-7).

Anal. Calcd for $C_{16}H_{22}N_2Fe$: C, 64.42; H, 7.45; N, 9.39. Found: C, 63.60; H, 7.01; N, 8.69.

**(*R*,*R*,$R_{pl}$)-15**

Hydrogenation of (*R*,*R*,$R_{pl}$)-**14** (190 mg) according to the procedure described above in MeOH (5.7 mL) with Pd/C (25 mg) gave 160 mg (93%) of (*R*,*R*,$R_{pl}$)-**15**; $[\alpha]_{589}^{20}$ +131 (*c* 1.0 × $10^{-1}$, $CH_2Cl_2$).

CD (*c* 7.9 × $10^{-5}$, $CH_2Cl_2$): Δε ($\lambda_{max}$) = –0.22 (258), +0.72 (276), –1.31 (300), +0.80 (339), –0.34 (407), +0.42 (462).

UV/Vis ($CH_2Cl_2$): $\lambda_{max}$ (ε) = 426 (350), 228 (12400).

Anal. Calcd for $C_{16}H_{20}N_4Fe$: C, 64.42; H, 7.45; N, 9.39. Found: C, 64.87; H, 7.47; N, 9.22.

**Catalytic Hydrogenation; General Procedure**

A Schlenk flask was charged with a solution of ketone (1.90 mmol) and chelate ligand (0.019 mmol) in anhyd degassed *i*-PrOH (3.4 mL). Then KOH (0.1 M solution, *i*-PrOH; 0.19 mL, 0.019 mmol) was added. This solution was then transferred via cannula into a Schlenk flask containing [Cp*Ru(cod)Cl] (7.4 mg, 0.019 mmol). The reaction mixture was stirred and evacuated until the solvent started to boil. A $H_2$ pressure of 2 bar was applied and the progress of the reaction followed by TLC or GC by taking samples. The solvent was removed in vacuo and the mixture filtered through a short column of silica gel ($Et_2O$–pentane). The hydrogenation products were identified by $^1H$ NMR spectroscopy and the absolute configuration of the major enantiomer was determined by comparison of the specific optical rotation with reference compounds (Table 1).

**Transfer Hydrogenation; General Procedure**

[(*p*-Cymene)$RuCl_2$]$_2$ (1.8 mg, 3.0 μmol), chelate ligand (12 μmol), and *t*-BuOK (2.7 mg, 24 μmol) were dissolved at ambient temperature in anhyd degassed *i*-PrOH (2 mL). The mixture was stirred for 45 min at r.t. and then a solution of the ketone (0.6 M in *i*-PrOH, 2 mL, 0.12 mmol) was added. The course of the reaction was monitored by GC and the ee values were determined by chiral GC.

***rac*-16**

A mixture of [(*p*-cymene)$RuCl_2$]$_2$ (41 mg, 0.067 mmol) and *rac*-**12a** (59 mg, 0.135 mmol) was dissolved in anhyd $CH_2Cl_2$ (6.9 mL). The mixture was stirred overnight at r.t., then the solvent was removed in vacuo. The product obtained was used for a series of crystallization experiments. Slow diffusion of $Et_2O$ vapor into a solution of the product in $CH_2Cl_2$ gave a few single crystals that were suitable for X-ray crystal structure analysis (CCDC 607478): formula $C_{36}H_{40}Cl_2FeNPRu$, *M* = 745.48, yellow crystal 0.25 × 0.10 × 0.10 mm, *a* = 9.898(1), *b* = 13.576(1), *c* = 14.349(1) Å, *α* = 108.36(1)°, *β* = 93.77(1)°, *γ* = 94.43(1), *V* = 1816.2(3) $Å^3$, $\rho_{calc}$ = 1.363 $gcm^{-3}$, μ = 1.030 $mm^{-1}$, empirical absorption correction (0.783 ≤ *T* ≤ 0.904), *Z* = 4, triclinic, space group *P*–1 (No. 2), λ = 0.71073 Å, *T* = 198 K, ω and φ scans, 20311 reflections collected (±*h*, ±*k*, ±*l*), [(sinθ)/λ] = 0.67 $Å^{-1}$, 8790 independent ($R_{int}$ = 0.059) and 7033 observed reflections [$I \geq 2\sigma(I)$], 383 refined parameters, *R*1 = 0.056, *wR*2 = 0.186, max. residual electron density 3.89 (–0.62) $eÅ^{-3}$, in a channel around x,0.5,0.5, could not be described in a chemically meaningful way, hydrogen atoms calculated and refined as riding atoms.

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