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Introduction

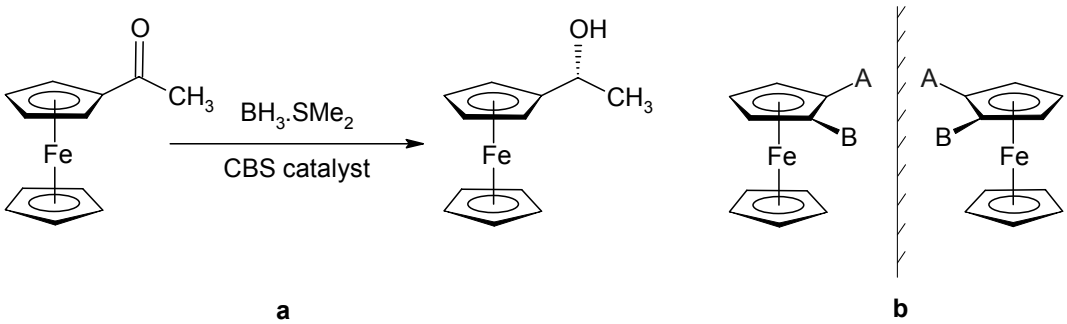
Investigations into catalytic processes represent one of the most perspective areas of contemporary chemical research. Continual effort over the past few decades brought about many innovations in this field. A particular attention has been paid to the development of catalysts capable of promoting the catalysed reactions with higher activity and selectivity, at milder conditions, using cheaper substrates and less toxic solvents, etc. Only such systems nowadays satisfy the demands for high effectiveness and economy, as well as for environmental tolerability of chemical processes at industrial scale.

Among other issues, the rational design of *ligands* for specific transition metal-mediated reactions is a significant objective of the current research in this area. In order to achieve the above-mentioned goals and to provide particular solutions for the applied science, the creation of a basis of detailed knowledge is required. Firstly, it is essential to understand as much as possible the individual reaction mechanisms, the role of the ligands and reaction conditions. As for the ligands, which often represent the crucial component of the catalytic system, the early research typically comprised the exploration of reactivity of a particular compound and synthetic routes allowing its preparation. Very soon it has been recognised that an access to a broad scope of ligands with varying properties (both steric and electronic) is desirable because of their potential utilisation in new reactions, where certain optimisation is usually required. Independently, however, coordination properties of the ligands should be investigated since the structural features of the prepared coordination compounds provide valuable information that often relates to the stereochemistry of catalytic intermediates.

Ferrocene-based donors[1] constitute a well established ligand class, which includes derivatives equipped with many different donor groups. The seemingly peculiar organometallic scaffold offers a great synthetic versatility, sufficient stability, and favourable geometry. Since its discovery[2] in the early 1950's, ferrocene attracted much attention of chemists, which in turn ensued in a great amount of research work that has been done on the synthesis of ferrocene derivatives and their further transformations. This opened an access to a large number of compounds, and also allowed to tune their properties in a broad range through structural modifications. An extraordinarily high stability (for an organometallic compound) is the characteristic feature of ferrocene, making the utilisation of its derivatives practically possible. From the chemical point of

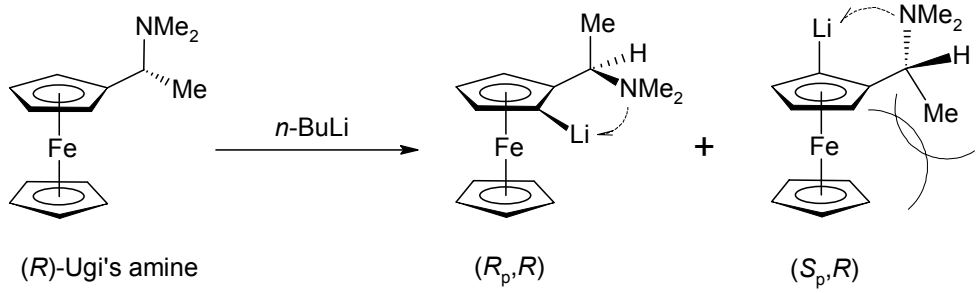
view, the ferrocene molecule disposes of aromatic cyclopentadienyl rings that are responsible for some properties and behaviour typical for other aromatic systems. As a substituent, the ferrocenyl group represents a strongly electron-donating moiety, capable of electronic conjugation. The electrochemical behaviour arising from the presence of the iron atom is also remarkable and often utilised property. Ferrocene/ferrocenium one-electron reversible redox couple can be influenced by attaching various substituents to the ferrocene unit. Moreover, changes in the redox potential of the ferrocene fragment connected to a studied molecule can serve as a valuable probing-tool at the molecular level. Such use of ferrocene moiety for "molecular probing" has developed in recent years into applications including molecular sensors and redox labels for a wide array of chemical species ranging from simple inorganic ions to biomolecules.[3] Another direction led to the development of redox-switchable catalysts.[4]

Finally, the unique steric properties of ferrocene result from the combination of several factors. On one hand, the ferrocene unit possesses conformational flexibility provided by the facile rotation of its cyclopentadienyl rings. On the other hand, it also has quite rigid cylindrical shape, which is not easily deformed by tilting of the aromatic rings from their mutually coplanar orientation. The above-described geometry of the ferrocene scaffold has important consequences in the possible formation of chiral derivatives. Naturally, the chirality can be introduced into the molecule simply by attaching a chiral substituent. The chirality centre can also be formed in an achiral substituent via an enantioselective transformation – e.g., by reduction of a carbonyl group in the presence of a chiral catalyst (see Scheme 1a).[5] More interestingly, however, the introduction of two different groups onto one cyclopentadienyl ring makes the molecule planar chiral (Scheme 1b).

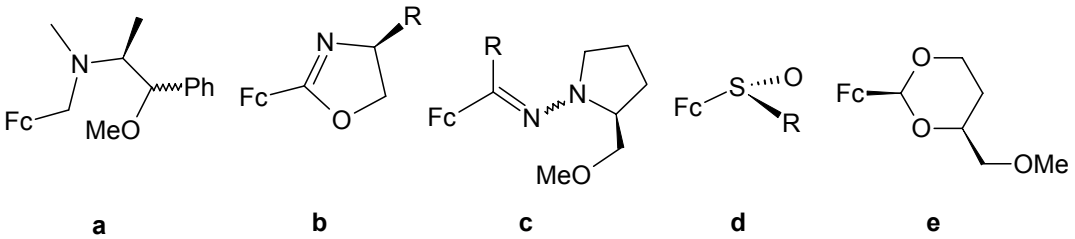


Scheme 1

Several synthetic protocols for the preparation of optically pure, planar chiral ferrocene derivatives have been described in the literature. Most frequently, the diastereoselective *ortho*-metalation approach is used, which, after reaction of the metalated species with an electrophile, affords 1,2-disubstituted ferrocenes combining planar and central chirality. Planar-only chiral derivatives are relatively less common. Their preparation usually proceeds also via *ortho*-metalation of chiral precursors. In terms of the classical methodology, chiral amines (e.g., *N*,*N*-dimethyl-1-ferrocenylethylamine, the so-called Ugi's amine[6] – Scheme 2) are the substrates of choice for the metalation reactions, though also other chiral groups such as oxazolines,[7] hydrazones,[8] sulfoxides,[9] acetals,[10] etc. were successfully employed (some representative examples of chiral *ortho*-directing groups are depicted in Scheme 3). Subsequent transformations of the side-groups provided an access to a number of chiral compounds. Many of them have been successfully applied as chiral ligands[11] in enantioselective catalysis of organic reactions producing a variety of fine chemicals, pharmaceuticals and other substances with biological activity that is usually connected with chirality of these compounds. The chiral induction provided by planar chiral ferrocene ligands often proved high, in many cases outperforming their conventional (organic) ligand analogues.

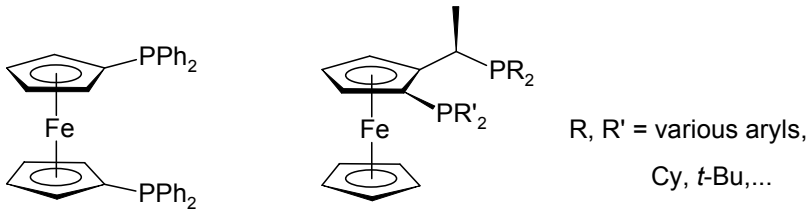


Scheme 2 **Diastereoselective *ortho*-lithiation of Ugi's amine. The (R_p,*R*)-diastereoisomer is formed preferentially for steric reasons, the (R_p,*R*):(S_p,*R*) ratio being about 96:4.**



Scheme 3 **Examples of chiral *ortho*-directing groups: (a) (ferrocenylmethyl)amine with chiral *O*-methylephedrine auxiliary,[12] (b) oxazoline, (c) SAMP (=*(S)*-1-amino-2-methoxymetylpyrrolidine) hydrazone, (d) sulfoxide, (e) cyclic acetal.**

Phosphanylferrocenes are undoubtedly the most frequently encountered ligands for catalytic applications among the ferrocene-derived donors. The simplest representatives have been known and studied thoroughly since 1970's. This is also the case of the most widely applied compound, the achiral diphosphane, 1,1'-bis(diphenylphosphanyl)ferrocene (dppf, Scheme 4).[13] This ligand was shown to bind transition metals in various coordination modes – as a monodentate, or bidentate (chelating or bridging) ligand. The catalytic potential of dppf was demonstrated in many reactions, namely carbon-carbon cross-coupling reactions (Suzuki-Miayura, Heck, Stille, Negishi, Kumada-Tamao), nucleophilic allylic substitution, and carbonylation catalysed by palladium complexes, hydrogenation and hydroformylation (on ruthenium or rhodium complexes), as well as many others.[13b–e]

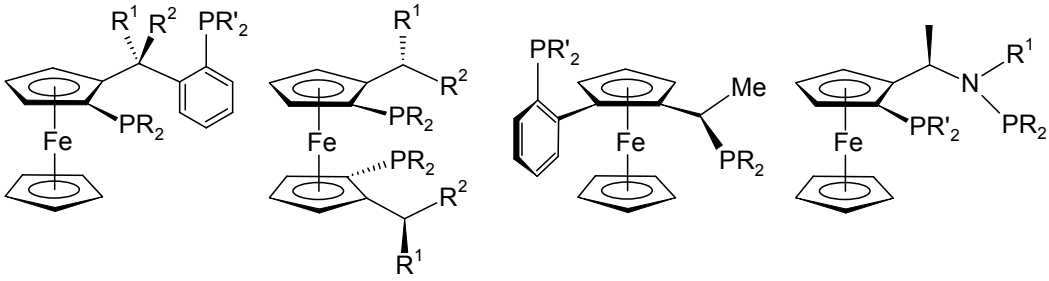


Scheme 4

Even more attention has been devoted to planar chiral diphosphanes, e.g., the Josiphos ligand family (Scheme 4), which was introduced by Togni et al. in 1994.[14] A versatile ligand design arises from the synthetic protocol based on the above described diastereoselective *ortho*-derivatisation of the chiral amine and the subsequent nucleophilic substitution of the amino group. This allows a step-wise introduction of two differently substituted phosphanyl groups, and thus, the formation of libraries of ligands with varying properties. Some of these compounds were applied to enantioselective catalysis with excellent results, while the scope of reactions is still increasing. There are at least four production scale industrial processes (and several other in the pilot stage), in which the Josiphos-type ligands are (or have been) used. Undoubtedly, the best known example is the enantioselective hydrogenation of *N*-aryl imine, catalysed by the iridium complex of the ligand, during the production of the herbicide (*S*)-Metolachlor.[15] Moreover, in recent years, the Josiphos moiety was immobilised onto organic and inorganic polymeric supports,[16]

attached to a dendrimeric backbone[17] or functionalised with hydrophilic groups to make the ligand water-soluble.[18]

Among other chiral ferrocene phosphanes, there are several successful ligand families with rather obscure traditional names (Scheme 5), such as Taniaphos[19] and Mandyphos/Ferriphos[20] (developed by the group of Knochel), Walphos[21] (introduced by Weissensteiner), or the aminophosphane-moiety-containing BoPhoz[22] first reported by Boaz. These ligands are nowadays generally available from commercial suppliers, and can be routinely used in the screening of catalytic systems to fit the specific reaction and substrate.

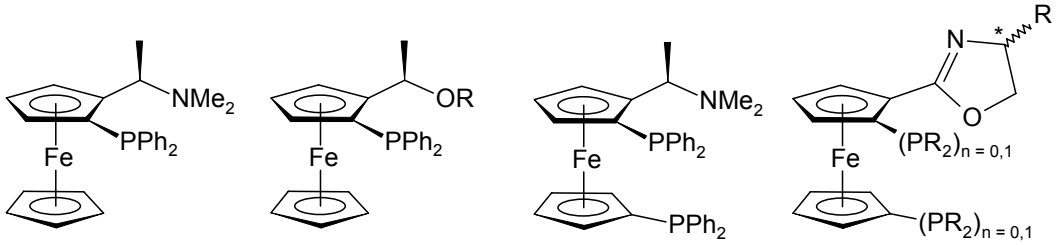


Taniaphos			Ferriphos/ Mandyphos	Walphos	BoPhoz
R[1]	*R*[2]	*generation*	$R^1 = NMe_2$, Alkyl	R, R' = Aryl, Cy	R^1 = Aryl, Me
NR_2	H	1st	R^2 = Aryl, Me		
H,MeO	MeO,H	2nd			
H	Alkyl	3rd			

Scheme 5

Polydentate ligands containing different donor groups according to the Pearson's theory of hard and soft acids and bases (HSAB)[23] – so called hybrid ligands – are quite common, mostly represented by functionalised phosphanes. The combination of donor atoms with a different coordination ability can often result in variable and interchangeable coordination modes and, in some cases, can impart the so-called hemilabile coordination.[24] The latter concept describes the situation when one donor group is bound firmly to the metal atom – typically phosphanyl group to a soft metal (usually used in catalysis) – while the other (hard-donor group) coordinates only weakly, and may temporarily create a coordination vacancy on the central atom after dissociation. Such behaviour has a pronounced effect on the course of catalysed reactions involving transition metal complexes equipped with these ligands. It has to be noted, that even uncoordinated donor groups can influence the structure and reactivity of catalytic intermediate species through weak interactions with substrates and/or reagents (hydrogen bonds, electrostatic or steric

interactions). Among hybrid phosphane ligands, those containing functional groups with nitrogen donor atom are most common. Oxygen donors have also gained a considerable importance, though the number of such ligands studied is still relatively lower.



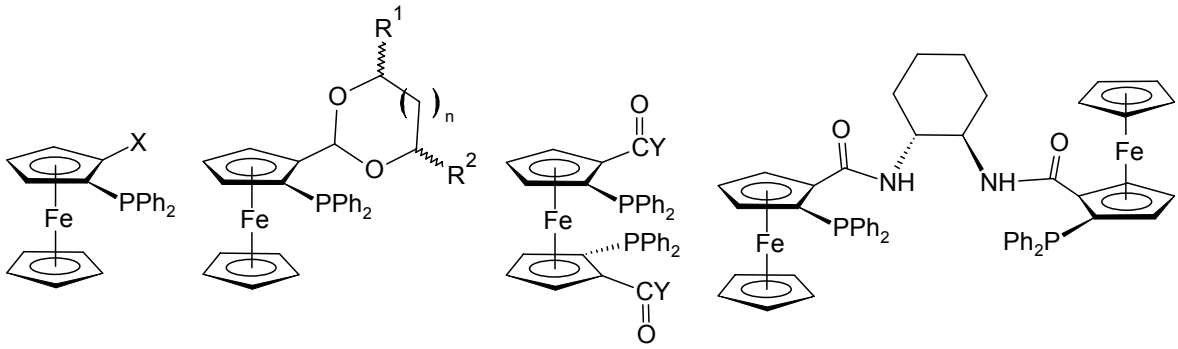
ppfa ppfOR bppfa **I**

Scheme 6

Typical examples of chiral ferrocene-based hybrid ligands are also represented by *P*,*N*-type donors. Usually, their preparation relies on the above described *ortho*-functionalisation of chiral amines. Ligands of the ppfa type (Scheme 6) are common representatives that were introduced by Kumada and Hayashi as early as in the 1970's.[25] Their work opened access towards a variety of new derivatives, and prompted a vigorous research activity motivated by the potential of these compounds in asymmetric catalysis. The dimethylamino group in ppfa was subsequently replaced by means of the nucleophilic substitution reaction with a number of groups containing not only nitrogen (variously substituted amines), but also oxygen (alcohols, esters, or alkoxides – ppfOR in Scheme 6; R = H, C(O)Me, or Me respectively), and particularly phosphorus (above-discussed diphosphanes, described later by Togni) or sulfur donor atoms. Moreover, the lithiation of Ugi's amine with an excess of butyl lithium and subsequent phosphanylation yields 1,1'-bis(phosphanyl)ferrocenes (bppfa type, Scheme 6), again optionally modified (after further transformations) with various functional groups.[26] Some of these chiral hybrid ligands were shown to be excellent catalyst components for nickel- or palladium-catalysed cross-coupling reactions of Grignard reagents with vinyl halides, palladium-catalysed allylic substitution, or rhodium-catalysed hydrogenation of ketones.[27]

Another interesting class of hybrid ligands are ferrocene phosphanyl-oxazolines (**I** in Scheme 6). The chiral dihydrooxazole moiety, which can be easily built up by the amidation of carboxylic group with *β*-aminoalcohols and subsequent cyclisation of the formed (β-hydroxyalkyl)amide,[28] serves as an efficient *ortho*-directing group, which

allows the diastereoselective preparation of 1,2-disubstituted planar chiral compounds. Being an outstandingly variable ligand family, phosphanyl-oxazolines with the ferrocene backbone have found manifold successful applications in enantioselective catalysis.[29] The broad scope of the tested reactions includes asymmetric C-C bond forming reactions as well as reductions of unsaturated substrates. Besides, the oxazoline moiety represents a carboxyl protecting group that makes these derivatives valuable synthons in the preparation of substituted ferrocenecarboxylic acids.[30]



II (X = CHO) **IV** **V** **VI**

III (X = CH_2OH)

Scheme 7 **Selected examples of chiral ferrocene *P,O*-ligands. For (IV): R^1, R^2 = Me, H; n = 0, 1. For (V): Y = OR, $NH(CH_2)_nOH$.**

Up to now, *O*-donor-containing chiral ferrocene phosphanes remained rather marginal topic, comprising only a limited number of compounds. Their structures were often derived from ppfa/bppfa type phosphanyl-amines, in which both the central and planar chirality is combined. Alcohols, ethers, and acetates prepared from ppfa/bppfa (depicted schematically in Scheme 6) are the most common examples. On the other hand, the preparation of *P,O*-ligands bearing *only* planar chirality is based on the use and subsequent transformation/removal of the chiral *ortho*-directing group or, much less frequently, on the utilisation of a chiral base[31] for the deprotonation/metalation of ferrocene cyclopentadienyl rings. The former approach was demonstrated, e.g., in the synthesis of optically pure 2-(diphenylphosphanyl)ferrocenecarboxaldehyde[32] (**II** in Scheme 7), which itself serves as a valuable precursor to many compounds including phosphanyl-alkenes[33] or phosphanyl-ferrocene acetals (**IV** in Scheme 7) equipped with additional central chirality elements.[34]

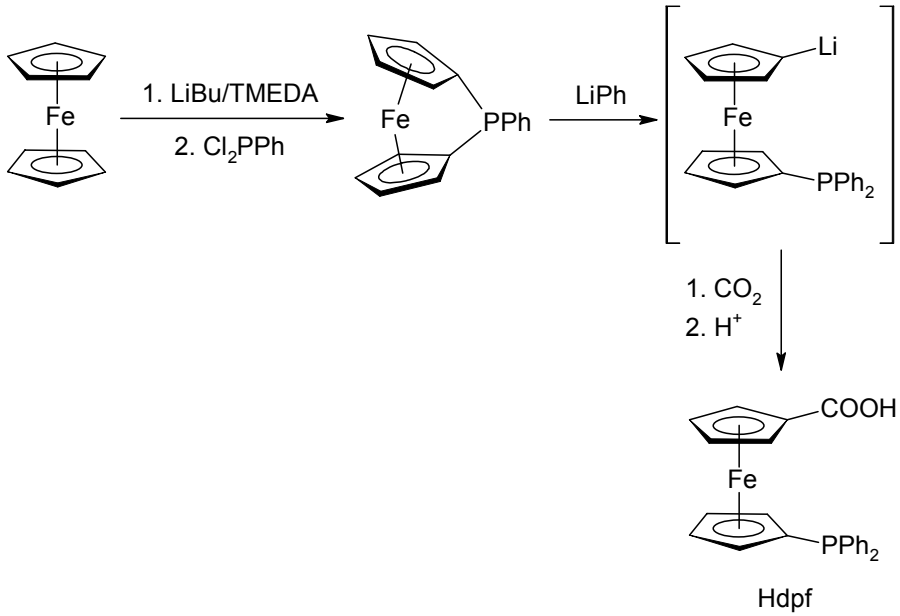
2-(Diphenylphosphanyl)ferrocenylmethanol[35] (**III** in Scheme 7) as another rare example of non-racemic planar chiral ferrocene *P*,*O*-donor, was also prepared via removal of the temporary chiral auxiliary ((*S*)-2-methoxymethylpyrrolidinyl) after the phosphanylation step. The same applies for C_2-symmetric phosphanyl-carboxylates and -carboxamides[36] (**V** in Scheme 7), as well as for 2-(diphenylphosphanyl)-ferrocenecarboxylic acid used in the preparation of Trost-type (chiral pocket) ligands (**VI** in Scheme 7),[37] that were all approached via the corresponding oxazoline derivatives.

Apart from the aforementioned hybrid ligands combining phosphorus and oxygen donor atoms, phosphanyl-carboxylic acids, together with some related derivatives thereof, gained also a certain attention. These compounds can be regarded as phosphanes modified with a polar carboxyl group that possibly allows for hemilabile coordination in different coordination modes (simple *O*-donor, *O*,*O'*-chelating or bridging group; in the protonated form, or as the respective carboxylate)[38] and can be easily converted into further polar derivatives such as esters and amides. As for the simple "organic" phosphanyl-carboxylic acids, their catalytic potential was demonstrated particularly in the nickel-catalysed oligomerisation of ethene that was successfully applied at the industrial scale.[39]

The first ferrocene-based phosphanyl-carboxylic acid, 1'-(diphenylphosphanyl)-ferrocenecarboxylic acid (Hdpf, Scheme 8), prepared by ferrocenophane-ring opening in (ferrocene-1,1'-diyl)phenylphosphine with phenyl lithium followed by carboxylation, was reported in 1996 by our group.[40] Since then, the chemistry of ferrocene carboxyphosphanes have been one of the key subjects in our research.[41]

In the following years, the complexation behaviour of Hdpf was thoroughly studied in order to establish the differences and similarities with organic phosphanyl-carboxylic acids and the related donor-uniform ferrocene ligands bearing either phosphanyl or carboxyl groups. Using various palladium(II) and platinum(II) sources, and Hdpf the expected square-planar complexes were formed, featuring the acid as a *P*-monodentate ligand. Thus, *trans*-[PdX_2(Hdpf-κ*P*)$_2$] (X = Cl, Br) resulted from the reaction of two molar equivalents of Hdpf with $K_2[PdCl_4]$, [Pd(cod)X_2], and [$Pd(PhCN)_2Cl_2$], while *trans*-[$PtCl_2$(Hdpf-κ*P*)$_2$] was prepared from $K_2[PtCl_4]$, as the thermodynamically more stable isomers. On the other hand, *cis*-[$PtCl_2$(Hdpf-κ*P*)$_2$] resulted as the kinetic product from the reaction of Hdpf with [Pt(cod)Cl_2].[42] Moreover, some palladium(II) complexes featuring the methyl ester of Hdpf with an *ortho*-metalated *N,N*-dimethyl(benzyl)amine as an

auxiliary ligand were prepared, structurally characterised, and utilised in Suzuki-Miayura cross-coupling reaction.[43]



Scheme 8

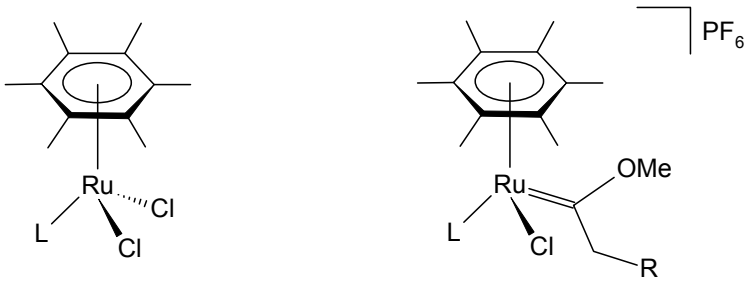
The reaction of Hdpf with nickel(II) salts was shown to afford complexes that tend, in contrast to the stable analogous palladium and platinum compounds, to dissociatively decompose in polar solvents. Following complexes were prepared starting from nickel(II) salts and Hdpf or its salt: paramagnetic $[NiX_2(Hdpf\text{-}\kappa P)_2]$ (X = Cl, Br, I), diamagnetic square planar isothiocyanato complex $[Ni(SCN)_2(Hdpf\text{-}\kappa P)_2]$, and finally the complex of the composition $[Ni(dpf)_2]$, which features the deprotonated phosphanyl-carboxylate ligand according to spectral and magnetic measurements, and is insoluble in common solvents presumably due to its polymeric nature.[44] A reaction of mercury(II) halides with Hdpf afforded $[HgX_2(Hdpf\text{-}\kappa P)_2]$ or $[HgX(\mu\text{-}X)(Hdpf\text{-}\kappa P)]_2$ complexes (X = Cl, Br, I) depending on the reaction stoichiometry. These complexes were also characterised by the X-ray diffraction, while NMR and electrochemical measurements revealed their tendency to undergo solvolysis in donor solvents.[45]

Complexes of group 6 metals $[M(CO)_5(Hdpf\text{-}\kappa P)]$, (M = Cr, Mo, W) were obtained either by the thermally-induced displacement of CO with Hdpf in hexacarbonyl complexes of respective metals, or by the substitution of the weakly coordinated solvent with Hdpf in the photochemically generated intermediates $[M(CO)_5(THF)]$.[46]

The tetrameric heterocubane $[Cu_4I_4(Hdpf\text{-}\kappa P)_4]\cdot 2CH_3CO_2H$, whose structure was corroborated by the X-ray diffraction, resulted from the reaction of Hdpf with copper(I)

iodide in acetic acid.[47] The solid-state structure of this complex features two hydrogen-bonded acetic acid molecules associated with the uncoordinated carboxyl groups, while the remaining two carboxyls form typical double hydrogen bridges between adjacent molecules.

Hdpf was also utilised in the synthesis of an extensive series of (methoxycarbene)(η^6-hexamethylbenzene)ruthenim(II) complexes bearing various phosphane ligands (**VIII**, Scheme 9). The starting [(η^6-C_6Me_6)$RuCl_2(PR_3)$] complexes **VII** were prepared by a bridge-cleavage reaction of the dimeric precursor [{(η^6-C_6Me_6)Ru(μ-Cl)Cl}$_2$] with the stoichiometric amount of the respective phosphane. Subsequently, the reaction of complexes **VII** with terminal alkynes in the presence of $NaPF_6$ and methanol yielded carbenes **VIII**. The whole series of carbenes together with dichloro(phosphanyl) complexes **VII** was studied by cyclic voltammetry. The measurements revealed electronic coupling between the interconnected Fe and Ru redox centres in the case that the ferrocene unit is connected via the coordinated phosphanyl group. On the other hand, the redox potential of the ferrocene unit, which is situated in the carbene part, remains unaffected as it is connected to ruthenium via a non-conjugated methylene linker.[48]



VII L = PMe_3, PPh_3, $FcPPh_2$, Hdpf

VIII L = see **VII**; R = H, Ph, Fc

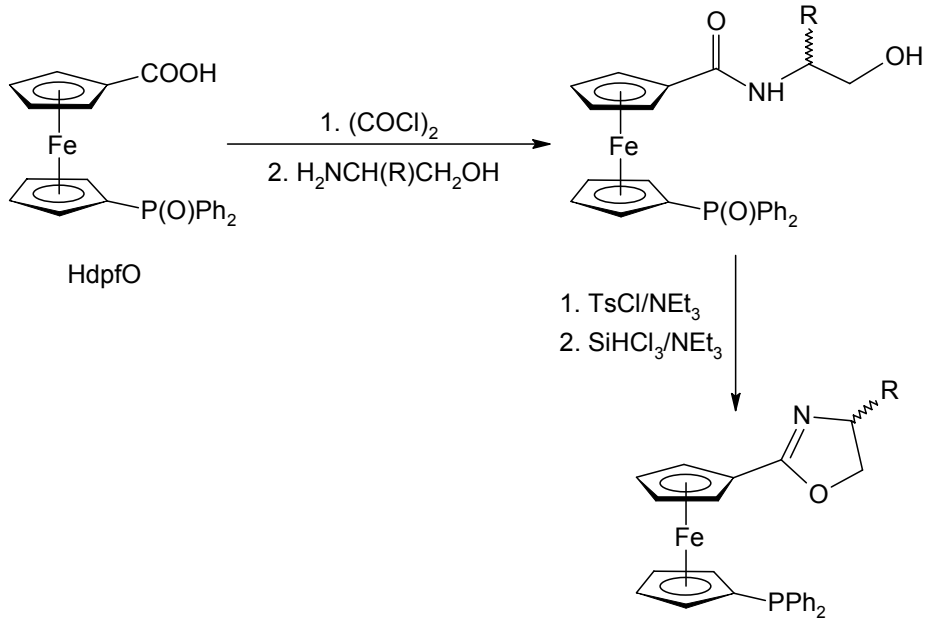
Scheme 9

A series of rhodium(I) complexes of Hdpf: *trans*-[Rh(Hdpf-κ*P*)$_2$X(CO)] (X = Cl, Br), *trans*-[Rh(dpf-κ^2*O*,*P*)(PR_3)(CO)] (PR_3 = PPh_3, PCy_3, $FcPPh_2$), and *trans*-[Rh(dpf-κ^2*O*,*P*)(Hdpf-κ*P*)(CO)], demonstrated the ability of the carboxyphosphane ligand to bind also as an *O*,*P*-chelating carboxylate.[49] Some of these rhodium complexes were shown to be effective, selective, and recyclable catalysts in hydroformylation of 1-hexene.[50]

A rare example of an exclusive carboxylate coordination of Hdpf is the paramagnetic complex [(η^5-C_5HMe_4)$_2$Ti(dpf- κ^2*O*,*O*′)], where the phosphanyl group is not

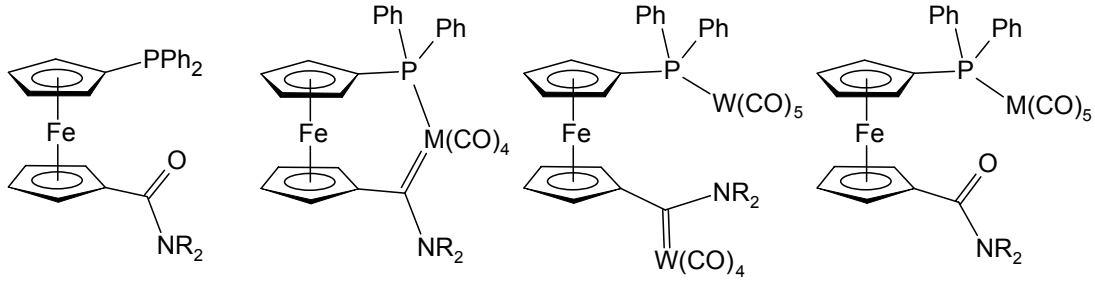
involved in the coordination to titanium, which has a character of hard Lewis acid, and therefore exerts a pronounced affinity towards *O*-donor ligands.[51] Another attempts to prepare compounds featuring a form of Hdpf as an *O*-donor resulted in the preparation of simple carboxylate salts. Upon reacting Hdpf with inorganic bases, salts of alkali metals or alkali earth metals, respectively, were obtained as was evidenced by the IR spectra, but the products were ill-defined amorphous materials, tending to retain solvents.[52]

Apart from the investigations made into the coordination chemistry of Hdpf, also its synthetic utility has been demonstrated. Simple esterification of Hdpf afforded methyl ester (Medpf),[40] while its reduction yielded the corresponding alcohol, 1'-(diphenylphosphanyl)-ferrocenylmethanol.[53] Even more attention has been devoted to various amides derived from Hdpf. The acid was used as a precursor, after protection of the phosphanyl group as the phosphane oxide, in the alternative preparation of chiral phosphanyloxazoline ligands. In this procedure, acyl chloride of HdpfO was reacted with chiral β-amino alcohols to yield amides that subsequently underwent oxazoline ring closure, and finally, the phosphanyl group was recovered by reduction (Scheme 10).[54]



Scheme 10

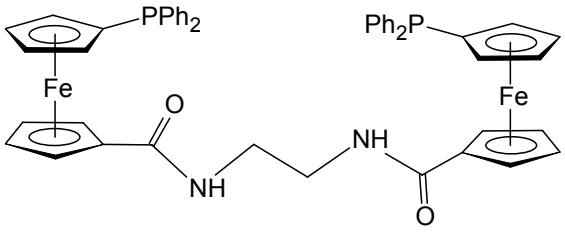
In another work, tertiary amides of Hdpf (**IX**, Scheme 11) were prepared by treating the acid with secondary amines in the presence of peptide-coupling agents (1-hydroxybenzotriazole/*N*-[3-(dimethylamino)propyl]-*N'*-ethylcarbodiimide). These amides were then utilised in the synthesis of Fischer-type carbenes of group-6 metals, chromium and tungsten. A different behaviour was observed for every metal in reactions with $[M(CO)_5]^{2-}$ (M = Cr, W): *P*-chelating carbenes **X** (M = Cr, W), the trinuclear complex **XI**, as well as *P*-monodentate carbonyl complexes **XII** (M = Cr, W) were isolated. The reaction with the carbonylate $[Fe(CO)_4]^{2-}$ afforded exclusively [Fe(**IX**-κ*P*)$(CO)_4$].[55]



IX **X** **XI** **XII**

Scheme 11

To evaluate the possible applicability of Hdpf amides, some selected representatives were tested as ligands for palladium-catalyzed Suzuki-Miayura reaction. For example, the bis(phosphanylferrocene) diamide **XIII** (Scheme 12) proved to be an efficient ligand for the coupling reaction of various aryl bromides with phenylboronic acid when combined with $Pd(OAc)_2$ to form the catalyst *in situ*. The diamide was further converted to the corresponding phosphane sulfide that was structurally characterised, and that exhibited significantly lower activity in the catalytic tests than the parent ligand.[56]

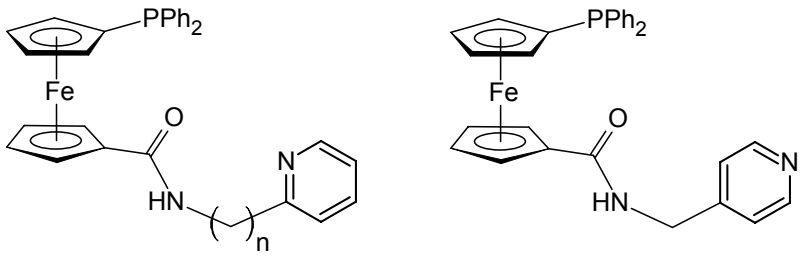


XIII

Scheme 12

For further catalytic studies, a series of (poly)amides bearing terminal 1'-(diphenyl)phosphanylferrocenyl groups was prepared by the amide coupling of Hdpf to first-generation poly(amido-amine) dendrimers (PAMAM). These dendrimeric compounds, together with their related mono- and diamide bearing only one or two phosphanylferrocene moieties, respectively, were tested as ligands in palladium-mediated cross-coupling reactions (Suzuki, Heck) with model substrates. The tests revealed positive influence of the dendrimeric assemblies, since the increasing number of phosphanyl termini resulted in somewhat faster reacting systems.[57]

Yet another Hdpf amides were prepared from amines containing pyridyl groups (Scheme 13). These functionalised (phosphanyl)ferrocene carboxamides possess a flexible donor arrangement, which allows for their variable coordination. This was manifested in the preparation of palladium(II) complexes of ligands **XIV** and **XV**, where different ligand-to-Pd ratios resulted in different types of compounds. Bisphosphanyl complexes $[PdCl_2(L\text{-}\kappa P)_2]$ were formed using 2:1 ligand/Pd ratio for both ligands on one hand, while for 1:1 ratio, the chelate complex $[PdCl_2(\mathbf{XIV}\text{-}\kappa^2 P,N)]$, where **XIV** acts as a *trans*-spanning *P*,*N*-donor, and the symmetric, *P*,*N*-bridged dimer $[(\mu\text{-}\mathbf{XV}\text{-}N,P)_2\{PdCl_2\}_2]$ in the case of **XV** were obtained. Furthermore, both these ligands were also successfully tested in the Suzuki-Miayura reaction.[58] More recently, the 2- and 4-pyridyl containing isomeric ligands (**XIV** and **XVI**) were subjected to a comparative coordination study towards group-12 metals, mercury and cadmium.[59] It was again shown that even a small change in the structure of the ligand may dramatically influence the structure of the resulting coordination assembly, since both one-dimensional coordination polymers as well as discrete oligonuclear structures were isolated, depending on the donor-sites spatial distribution of the respective ligand. Moreover, extensive hydrogen-bonding interactions were found in the solid state, forming thus well-defined supramolecular assemblies.

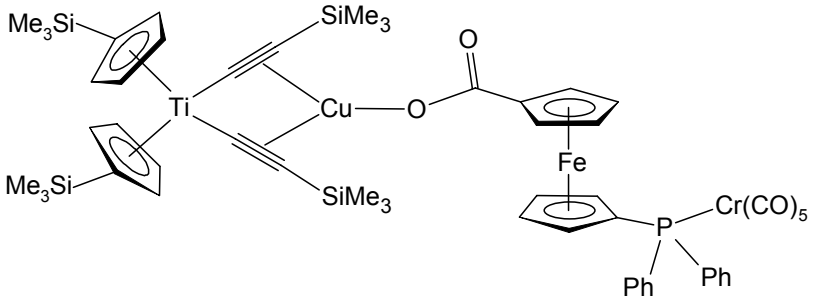


n = 1: **XIV**
n = 2: **XV**

XVI

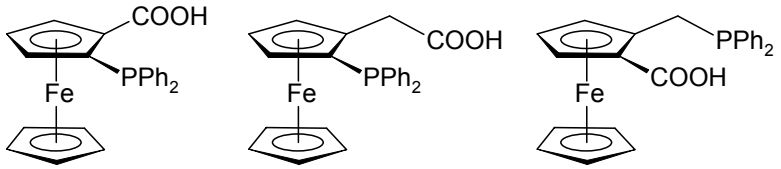
Scheme 13

Hdpf was also used, together with simple ferrocene carboxylic acids (FcCOOH, $Fc(CH_2)_2COOH$, FcCH=CHCOOH) as a building block in the preparation of heteromultimetallic transition metal complexes. Up to four different metals were incorporated into the molecule upon a stepwise connection of organometallic fragments (Scheme 14). For instance, compound **XVII** was prepared by reacting [{(η^5-$C_5H_4SiMe_3)_2Ti(\mu$-σ,π-$C{\equiv}CSiMe_3)_2$}CuMe] with [$Cr(CO)_5$(Hdpf-κP)].[60]



XVII

Scheme 14

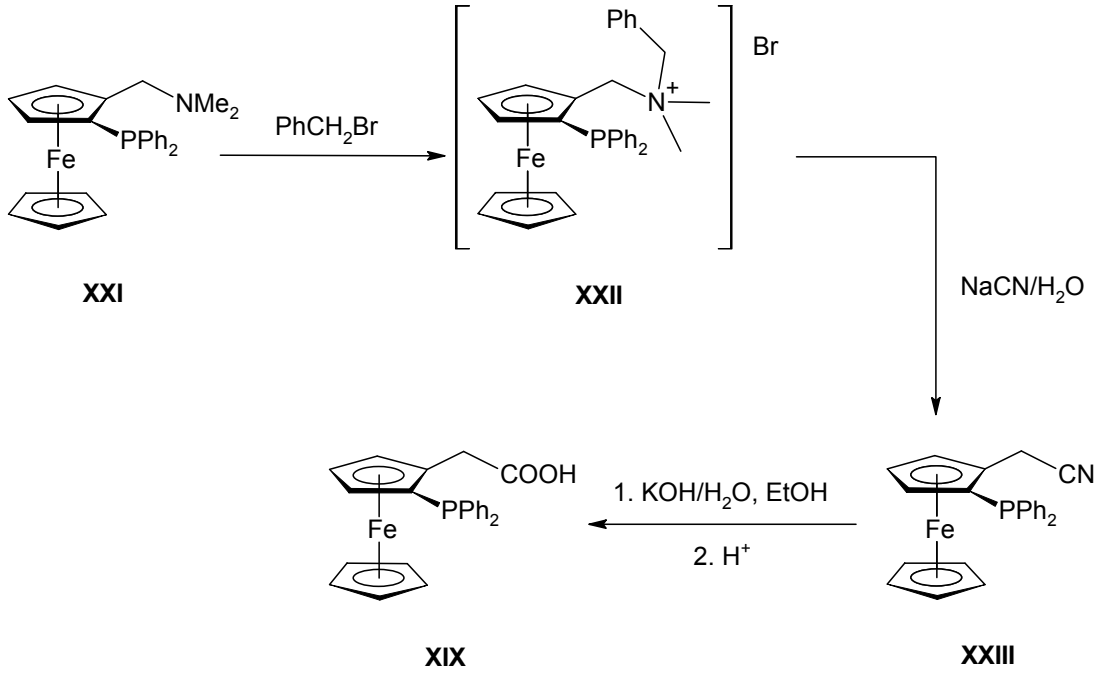


XVIII **XIX** **XX**

Scheme 15

In addition to Hdpf, other ferrocene-based phosphanyl-carboxylic acids were synthesised and studied in our group. As evident from their structures (Scheme 15), these compounds possess planar chirality arising from the one disubstituted cyclopentadienyl ring. The first example, 2-(diphenylphosphanyl)ferrocenecarboxylic acid, (S_p)-**XVIII**, a planar chiral isomer of Hdpf, was prepared in the optically pure form from the chiral oxazoline precursor (see above).[30,37b] The coordination behaviour of (S_p)-**XVIII** was examined for (arene)ruthenium(II) complexes, featuring the respective phosphanyl-carboxylate. A kinetic mixture of diastereoisomeric chelate complexes resulted from the reaction of the dimeric Ru(II) precursor [{Ru(μ-Cl)Cl(η^6-*p*-cymene)}$_2$] and the *in situ*

generated potassium salt of **XVIII** (formed by the deprotonation of the acid with KO*t*-Bu). After several days, a spontaneous epimerization occurred, and the thermodynamically preferred (R_{Ru},S_p)-[RuCl(**XVIII**-κ^2*O*,*P*)] isomer was isolated and structurally characterised.[30b]

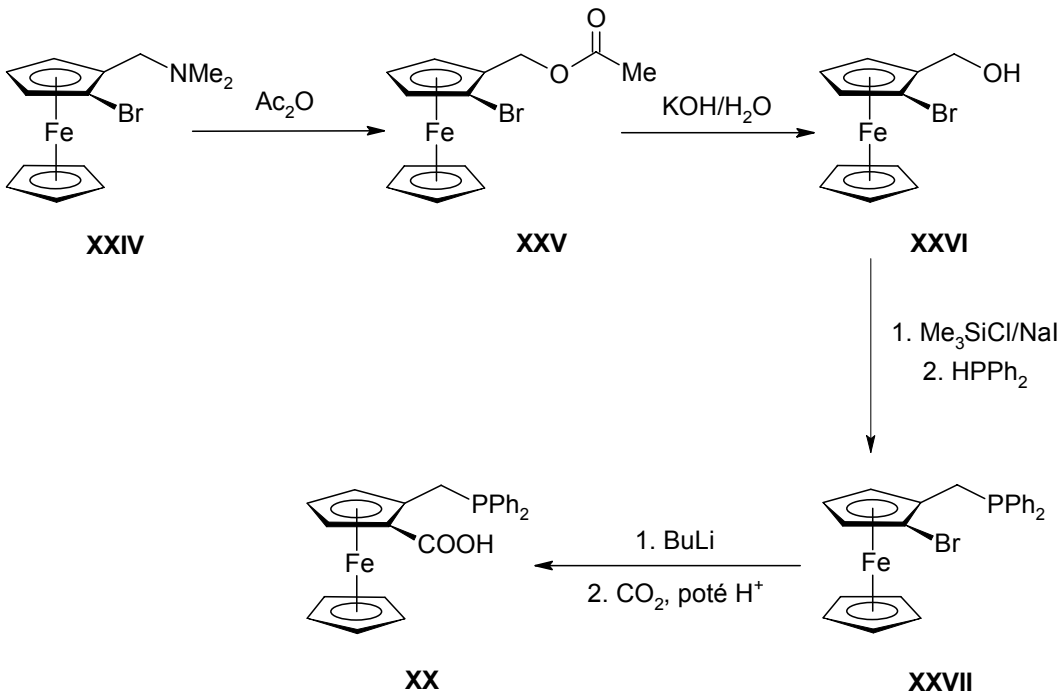


XXI **XXII** **XIX** **XXIII**

Scheme 16

The two isomeric acids: *rac*-[2-(diphenylphosphanyl)ferrocenyl]acetic acid (**XIX**), and *rac*-2-[(diphenylphosphanyl)methyl]ferrocenecarboxylic acid (**XX**) represent another extension of the ferrocene carboxyphosphane chemistry, which was aimed at the exploration of differences in ligating abilities of structurally related compounds, comparison of their structural features, as well as at the development of synthetic pathways to new compounds. Acid **XIX** was prepared in three steps from the known *rac*-{[(2-diphenylphosphanyl)ferrocenyl]methyl}dimethylamine (**XXI**) via the corresponding alkylammonium salt (**XXII**) and nitrile (**XXIII**). Nitrile **XXIII** was hydrolysed under basic conditions to give acid **XIX** (Scheme 16). The coordination ability of **XIX** was probed in palladium(II) complexes. Starting with the dimeric palladium precursor *trans*-[{Pd(μ-Cl)($C_6H_4CH_2NMe_2$-κ^2C^1,*P*)}$_2$], a series of complexes featuring the deprotonated acid or its methyl ester, and the *ortho*-metalated *N*,*N*-dimethyl(benzyl)amine as an auxiliary ligand was obtained. The deprotonated acid **XIX** coordinated as a chelate, whereas its methyl ester adopted the expected *P*-monodentate coordination, which was changed to the *O*,*P*-

chelating mode after removal of the chloride ligand with a silver(I) salt.[61] Moreover, the activated methylene group of the methyl ester of **XIX** was deprotonated by the action of a strong base, and this way another chelating coordination of the ligand was achieved.[62] Another coordination mode for deprotonated **XIX** was observed in the carboxylate-bridged dipalladium(II) complex, where the coordination of the phosphanyl group to Pd is accompanied by a bridging arrangement of both carboxylate groups, enabling the ligand to utilise *all* possible donor atoms in coordination.[63]



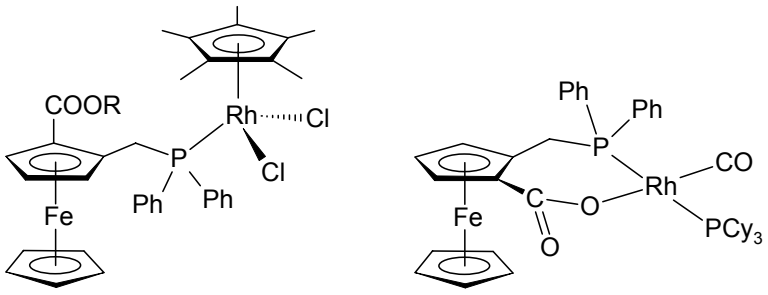
XXIV **XXV** **XXVI** **XX** **XXVII**

Scheme 17

Acid **XX**, isomeric to **XIX**, was prepared in a different manner starting from *rac*-[2-(bromoferrocenyl)methyl]dimethylamine (**XXIV**, Scheme 17). The amine was first converted by the transformations of the amino group via acetate (**XXV**) to alcohol (**XXVI**). Then, the bromo alcohol **XXVI** was phosphanylated upon treating with Me_3SiCl/NaI and Ph_2PH in acetonitrile, and the resulting phosphanyl bromide **XXVII** was consecutively lithiated with LiBu and carboxylated with carbon dioxide to afford, after acidification **XX**. The acid was further derivatised on both the carboxyl, and phosphanyl groups to obtain the corresponding methyl ester, phosphane oxide and sulfide, respectively.

The coordination of **XX** and its methyl ester was studied in rhodium complexes. The rhodium(III) complexes with *P*-monodentate ligands (**XXVIII** in Scheme 18; R = H,

Me) were prepared by bridge cleavage from [{Rh(μ-Cl)Cl(η^5-C_5Me_5)}$_2$]. Attempts to synthesize *O*,*P*-chelated complexes by treating the former complexes with bases or by halide removal failed but, finally, the *O*,*P*-chelating coordination of **XX** in the anionic form was achieved in a rhodium(I) complex **XXIX**.[64]



XXVIII **XXIX**

Scheme 18

More recently, all the acids Hdpf, **XVIII**, **XIX**, and **XX** were utilised either as chelating phosphanyl-carboxylates, or *P*-monodentate acids as ligands in palladium(II) complexes, some of which were tested as catalyst precursors in the palladium mediated semialternating CO–ethylene copolymerisation. The obtained results were rather modest in comparison to previously described systems. The extra-ethylene incorporation in the produced semialternating polyketone reached a maximum value of 4.3% The processes under catalytic-reaction conditions were followed by *in situ* NMR spectroscopy, which revealed an important evidence for the protonation of the carboxyl group in the neutral chelate complexes, and the formation of β-chelates involving the propagating polyketone chain.[65]

As a contribution to the previous work and as a key subject of my Ph.D. thesis, the scope of ferrocene carboxyphosphanes and their related derivatives was extended towards novel chiral compounds possessing planar chirality. The chemical behaviour and coordination ability of the newly prepared ligands towards catalytically relevant transition metals were investigated and their catalytic potential was probed in selected enantioselective metal-mediated organic reactions on model substrates. Furthermore, during this research, a synthetic approach comprising the diastereoselective deprotonation of activated methylene groups of planar chiral ferrocene derivatives was developed, opening new or alternative pathways to new chiral ferrocene ligands.

Aims of the thesis

The work described in the presented thesis was aimed at the preparation and study of chiral ferrocene based phosphanyl-carboxylic ligands. The primary objective was to design and prepare new compounds of this class utilising preferably approaches that lead to optically pure chiral products. The investigation of coordination properties of the prepared compounds was an integral part of the planned research. Yet another goal was to provide preliminary outlook towards possible applications that were seen mostly in asymmetric catalysis. According to numerous reports, it is well documented that chiral ferrocene ligands can act as catalyst components that effectively induce enantioselectivity in catalysed reactions. Therefore, the prepared compounds were intended for testing in selected model asymmetric, transition metal-mediated reactions to demonstrate their eventual utility. As a model reaction for catalytic tests of relevant ligands was finally (after initial experiments) chosen the palladium mediated enantioselective allylic alkylation.[66]

The scheduled project comprised the preparation of (Scheme 19):

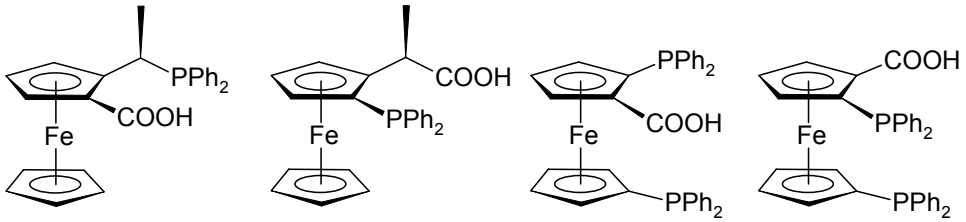
a) (R_p)-2-[(*R*)-1-(diphenylphosphanyl)ethyl]ferrocenecarboxylic acid (**1**), a chiral homologue to compound **XX** (see Scheme 15);

b) (*S*)-2-[(S_p)-2-(diphenylphosphanyl)ferrocenyl]propionic acid (**2**), an isomer to **1**;

c) both enantiomers of 1′,2-bis(diphenylphosphanyl)ferrocene-1-carboxylic acid (Hdpc), a planar chiral carboxylated analogue of dppf;

d) secondary amides bearing achiral and chiral *N*-substituents derived from the above listed, as well as from other previously described ferrocene phosphanyl-carboxylic acids;

e) complexes of the prepared ligands with catalytically relevant transition metals

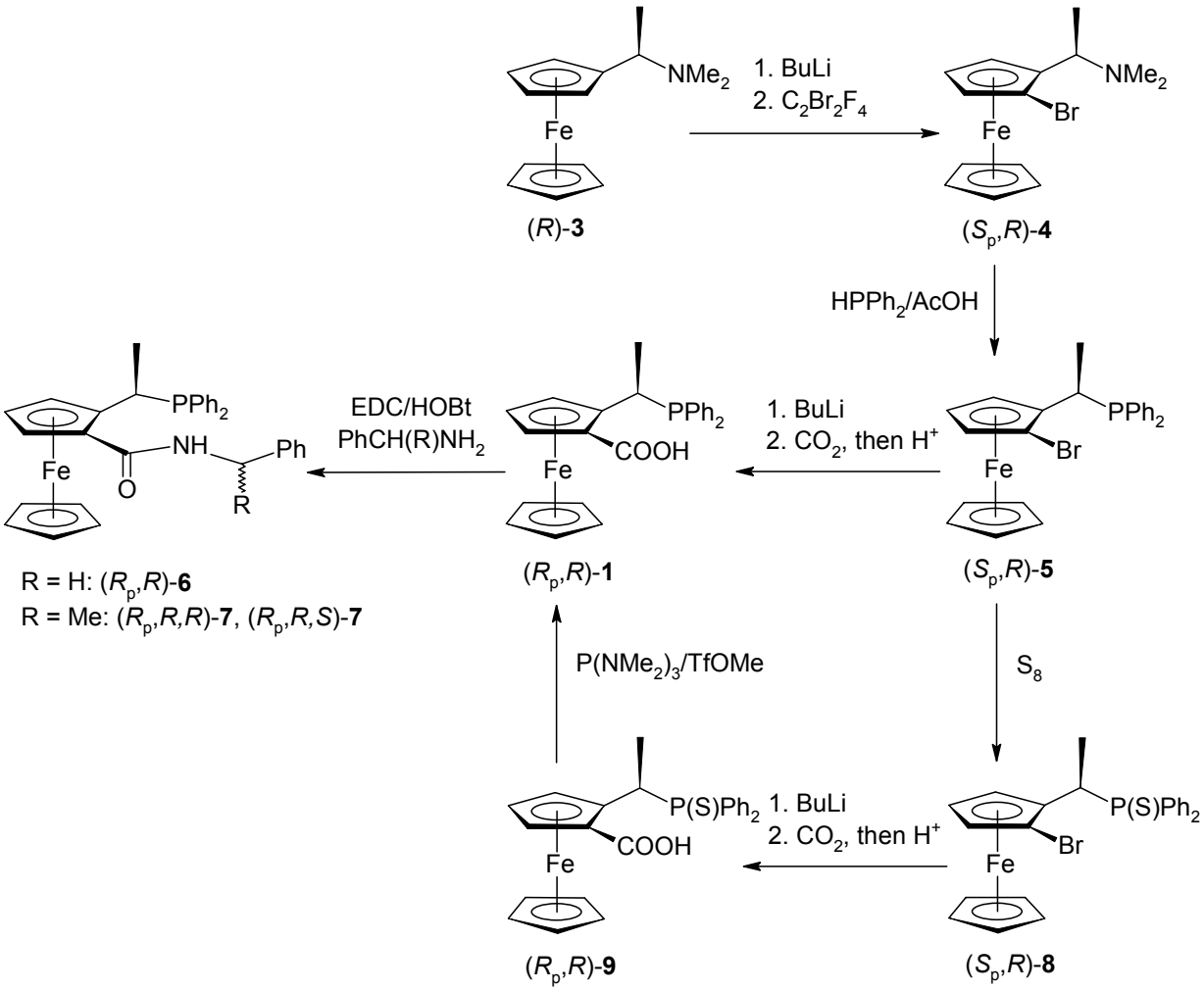


(R_p,*R*)-**1** (S_p,*S*)-**2** (R_p)-Hdpc (S_p)-Hdpc

Scheme 19

A concise summary of results

In the first part of my Ph.D. project, (R_p)-2-[(*R*)-1-(diphenylphosphanyl)ethyl]ferrocene-carboxylic acid (**1**, Scheme 20; Appendix 1), a ligand combining planar and central chirality, was synthesised in optically pure form. Acid **1** is a homologue to the previously reported racemic 2-[(diphenylphosphanyl)methyl]ferrocenecarboxylic acid (**XX**, see Scheme 15), which possesses only planar chirality. Synthesis of **1** began with diastereoselective *ortho*-lithiation and a subsequent bromination of the chiral amine **3** to give bromo-amine **4**. The following nucleophilic substitution of the amine group in **4** with diphenylphosphanyl group to form tertiary phosphane **5** proceeded with a complete retention of configuration at the chiral centre.

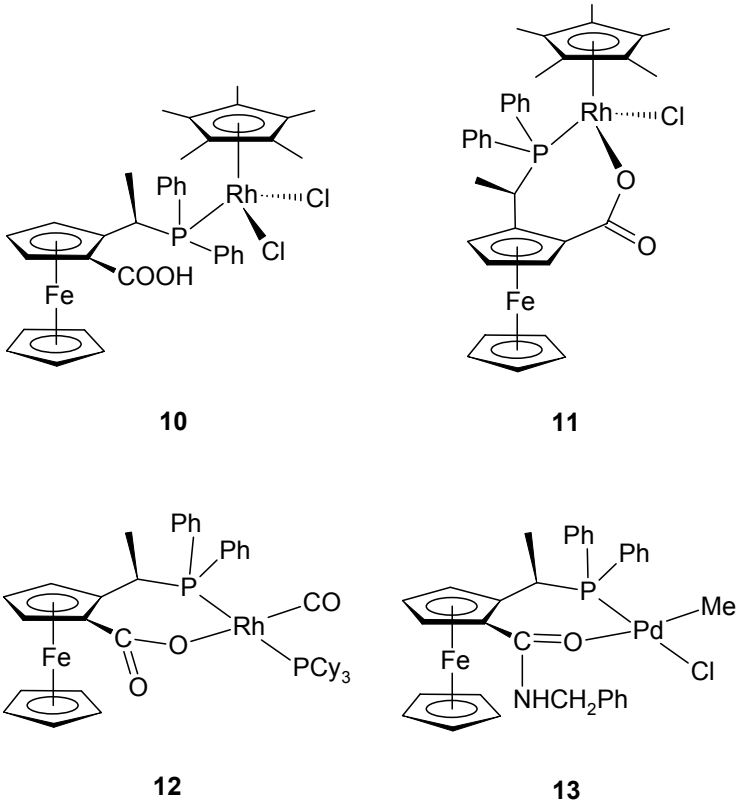


Scheme 20

These transformations were previously described by Giambastiani et al.[67] In the last step, bromide **5** was lithiated and the intermediate immediately carboxylated with an excess of solid carbon dioxide. Subsequent acidification provided acid **1** in 84 % yield after chromatography.

An alternative route to **1** was devised involving protection of the phosphane group. Bromide **5** was first reacted with sulfur to give the corresponding phosphane sulfide **8** which, after lithiation and carboxylation gave acid **9**. The deprotection of **8** was achieved with tris(dimethylamino)phosphane/methyl triflate.

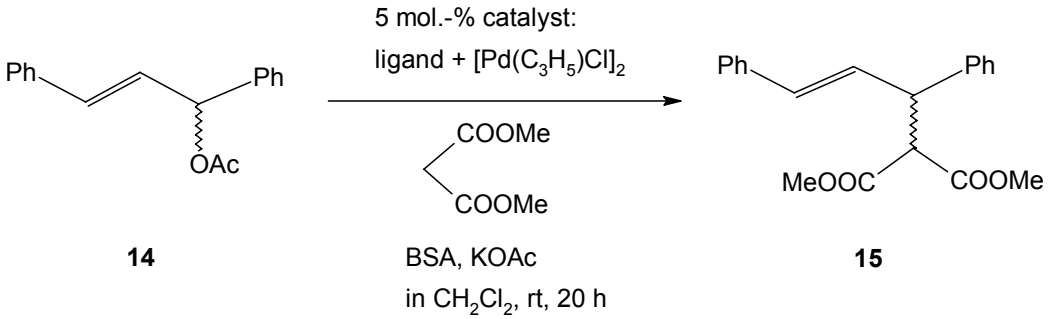
Modifications at both functional groups in **1** afforded a series of closely related derivatives. Apart from the above mentioned phosphane sulphide **9**, also phosphane oxide was prepared and its solid state structure determined by X-ray diffraction analysis. Finally, amidation of the carboxyl group with both achiral and chiral amines yielded amides **6** and **7**, respectively.



Scheme 21

In order to study coordination properties of **1** and related compounds, some rhodium complexes were prepared. Firstly, a bridge-cleavage of [{Rh(μ-Cl)Cl(η^5-C_5Me_5)}$_2$] with **1** gave complex **10** (Scheme 21) featuring *P*-monodentate **1**. Compound **10** underwent smooth conversion to phosphanyl-carboxylate complex **11** upon treatment with silica gel or alumina. An *O,P*-chelating coordination of the phosphanyl-carboxylate was also achieved in the rhodium(I) complex **12** that resulted from acid-base displacement of acetylacetonate ligand in [Rh(acac)(CO)(PCy_3)]. Solid-state structures of complexes **10** and **12** were determined by single-crystal X-ray diffraction The coordination behaviour of amides was probed on palladium(II). Thus, amide **6** displaced the cycloocta-1,5-diene (cod) ligand in [PdCl(Me)(cod)], affording the chelate complex **13**, the crystal structure of which was established by the X-ray diffraction.

With the aim to probe catalytic properties of the newly prepared ligands (acid **1**, and its amides **6** and **7**) in enantioselective catalysis, two asymmetric reactions were chosen: rhodium-catalysed hydrogenation of methyl β-acetamidocinnamate,[68] and palladium-catalysed allylic alkylation[66] of racemic (*E*)-1,3-diphenylprop-2-en-1-yl acetate (**14**) with dimethyl malonate anion (Scheme 22). While the first reaction did not proceed at all with our catalytic systems, the latter one provided valuable information about the influence of different chirality sources on the rate and selectivity of the reaction. The results are summarised in Table 1. Basically, the *ee* (enantiomeric excess) values obtained with these catalytic systems were inferior to those reported for the prominent ligand types such as (phosphanyl-ferrocenyl)oxazolines or Josiphos ligands but, on the other hand, a clear evidence for synergic effects of both chirality elements and the positive influence on the reaction selectivity upon the introduction of the amide moiety was observed.



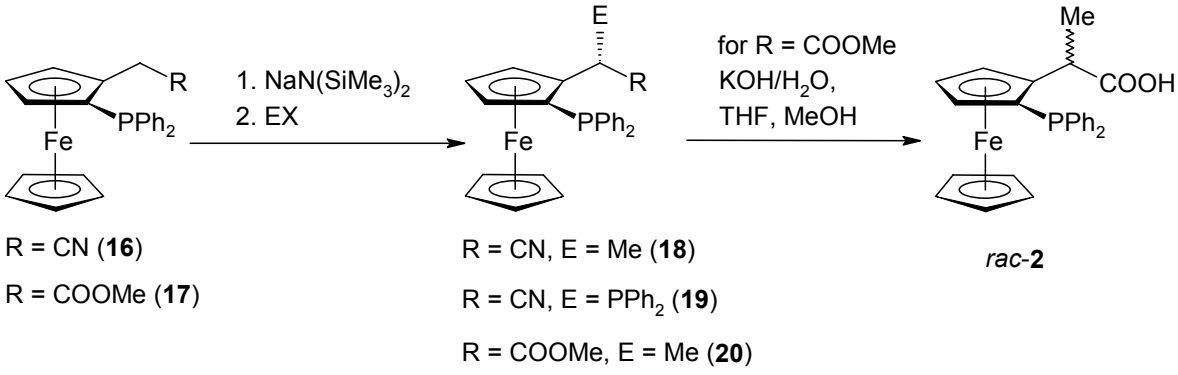
Scheme 22

Table 1 Asymmetric allylic alkylation with ligands 1, 6, 7 (For details see Apendix 1)

Entry	Ligand	conversion (isolated yield) [%][a]	*ee* [%] (configuration)[b]
1	(R_p,*R*)-**1**	100 (94)	10 (*S*)
2	(R_p,*R*)-**6**	55	41 (*R*)
3	(R_p,*R*,*R*)-**7**	42	43 (*R*)
4	(R_p,*R*,*S*)-**7**	22	35 (*R*)

[a] Conversion determined by ^{1}H NMR spectroscopy.
[b] Absolute configuration assigned on the basis of sign of the optical rotation.

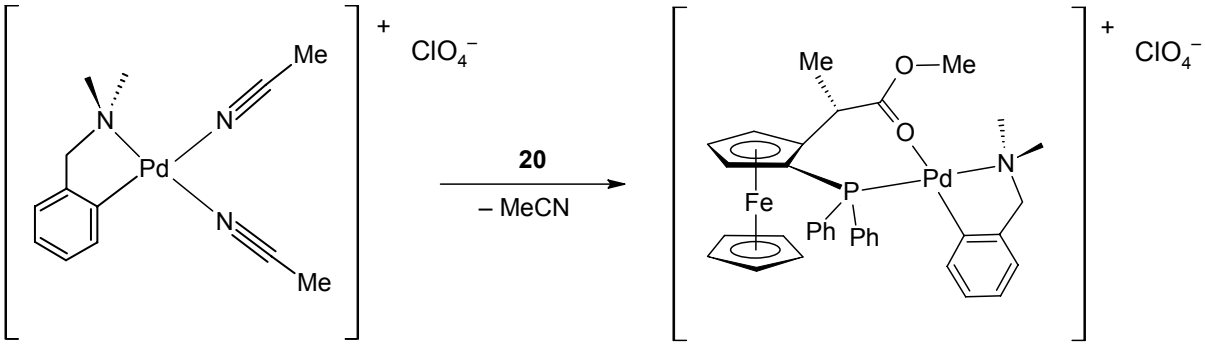
The next part of the work (Appendix 2) was focused on the preparation of (*S*)-2-[(S_p)-2-(diphenylphosphanyl)ferrocenyl]propionic acid (**2**), a homologue to previously prepared [2-(diphenylphosphanyl)ferrocenyl]acetic acid (**XIX**, see Scheme 15). The application of a similar synthetic procedure as for **XIX** was not successful in this case due to a different reactivity of some reaction intermediates. Instead, an alternative approach had to be used, leading to racemic but diastereomerically pure products. It was found, that α-deprotonation of racemic [2-(diphenylphosphanyl)ferrocenyl]acetonitrile (**16**) with $NaN(SiMe_3)_2$ proceeds with a high diastereoselectivity, and opens a route to products **18** and **19** via a subsequent reactions of the formed carbanion with electrophiles (Scheme 23).



Scheme 23

Since hydrolysis of nitriles proved to be difficult, other possible routes to acid **21** were studied (Appendix 3). It was found, that the deprotonation of an ester **17** is also possible and that it proceeds with a high diastereoselectivity. The resulting ester **20** was

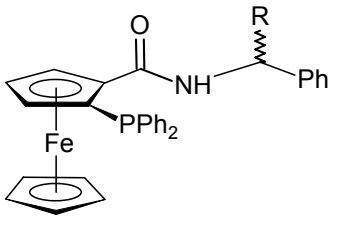
utilised in the preparation of the cationic chelate palladium complex **22** (Scheme 24). However, the hydrolysis of ester **20** was shown to be complicated by racemisation at the newly created stereogenic carbon atom and by concomitant oxidation of the phosphanyl group.



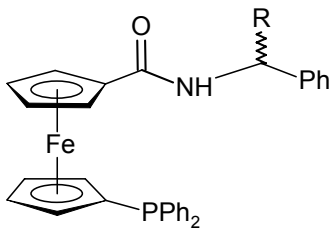
22

Scheme 24

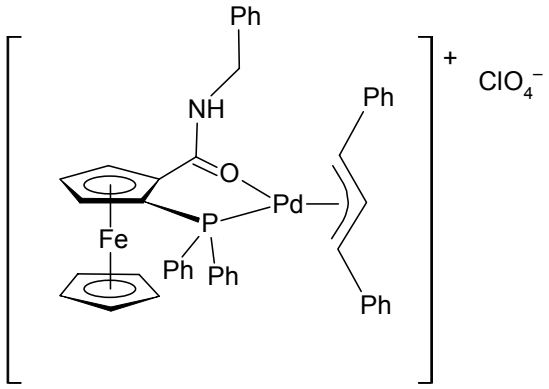
In the following work (Appendix 4), the attention turned back to the development of ligands for asymmetric allylic alkylation. Being encouraged by the previous results, we decided to extend the range of compounds tested in the aforementioned reaction utilising amides of the known ferrocene based phosphanyl-carboxylic acids. Thus, (S_p)-2-(diphenylphosphanyl)ferrocenecarboxylic acid itself ((S_p)-**XVIII**, Scheme 15), its amides (**23**, Scheme 25), as well as two other chiral amides (**24**) derived from Hdpf, were involved in the testing. The results (summarised in Table 2) clearly indicated the dominant role of planar chirality on the stereoselectivity of the reaction, since amides **24** exhibited no stereogenic induction at all, while their planar chiral counterparts gave moderate to good *ee*'s. Subsequent modification of reaction conditions allowed for *ee* as high as 90 % with ligand **23a** (for complete results, see Appendix 4). The suggested reaction mechanism for this ligand was confronted with the NMR spectroscopic and X-ray structural data of the model complex [Pd(η^3-1,3-$Ph_2C_3H_3$){(S_p)-**23a**-κ^2*O,P*}]ClO_4 (**25**, Scheme 25).



23a R = H
23b (*R*)-Me
23c (*S*)-Me



24a R = (*R*)-Me
24b (*S*)-Me



25

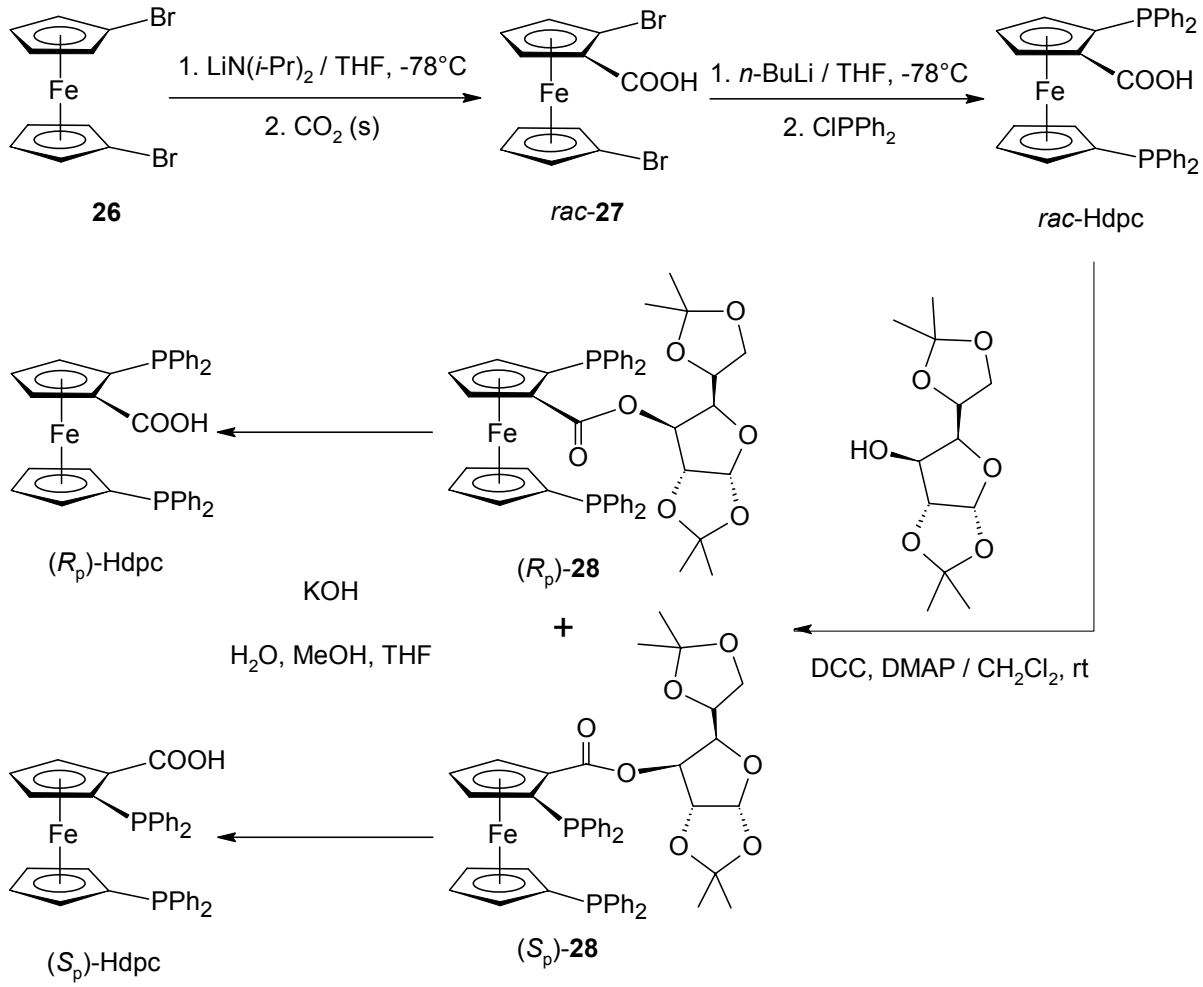
Scheme 25

Table 2 Asymmetric allylic alkylation with ligands XVIII, 23, 24 (For details see Apendix 4)

Entry	Ligand	*T*	Time	Additive	Conversion[a]	*ee* (%)[b]
1	(S_p)-**XVIII**	22	20	KOAc	100 (91)	50 [*R*]
2	(S_p)-**23a**	22	20	KOAc	100 (91)	58 [*R*]
3	(*R*,S_p)-**23b**	22	20	KOAc	100 (97)	49 [*R*]
4	(*S*,S_p)-**23c**	22	20	KOAc	100 (95)	21 [*R*]
5	(*R*)-**24a**	22	20	KOAc	100 (90)	0
6	(*S*)-**24b**	22	20	KOAc	100 (92)	0
7	(S_p)-**23a**	22	20	none	85	90 [*R*]
8	(S_p)-**23a**	22	20	LiOAc	100	48 [*R*]
9	(S_p)-**23a**	22	20	NaOAc	100	84 [*R*]
10	(S_p)-**23a**	0	42	NaOAc	41	88 [*R*]
11	(S_p)-**23a**	22	20	KOAc	100	58 [*R*]
12	(S_p)-**23a**	22	20	RbOAc	100	44 [*R*]
13	(S_p)-**23a**	22	20	CsOAc	100	49 [*R*]

[a] Conversion determined by ^{1}H NMR spectroscopy.
[b] Absolute configuration assigned on the basis of sign of the optical rotation.

As a next step in the exploration of carboxyphosphane ligands, a *mono*carboxylated dppf derivative, 1′,2-bis(diphenylphosphanyl)ferrocene-1-carboxylic acid (Hdpc) was prepared and studied (Appendix 5). Hdpc fills the gap left between Hdpf, its planar chiral isomer **XVIII** (Scheme 15), and C_2-symmetric 2,2′-bis(diphenylphosphanyl)ferrocene-1,1′-dicarboxylic acid.[69] The synthetic route leading to Hdpc is depicted in Scheme 26.

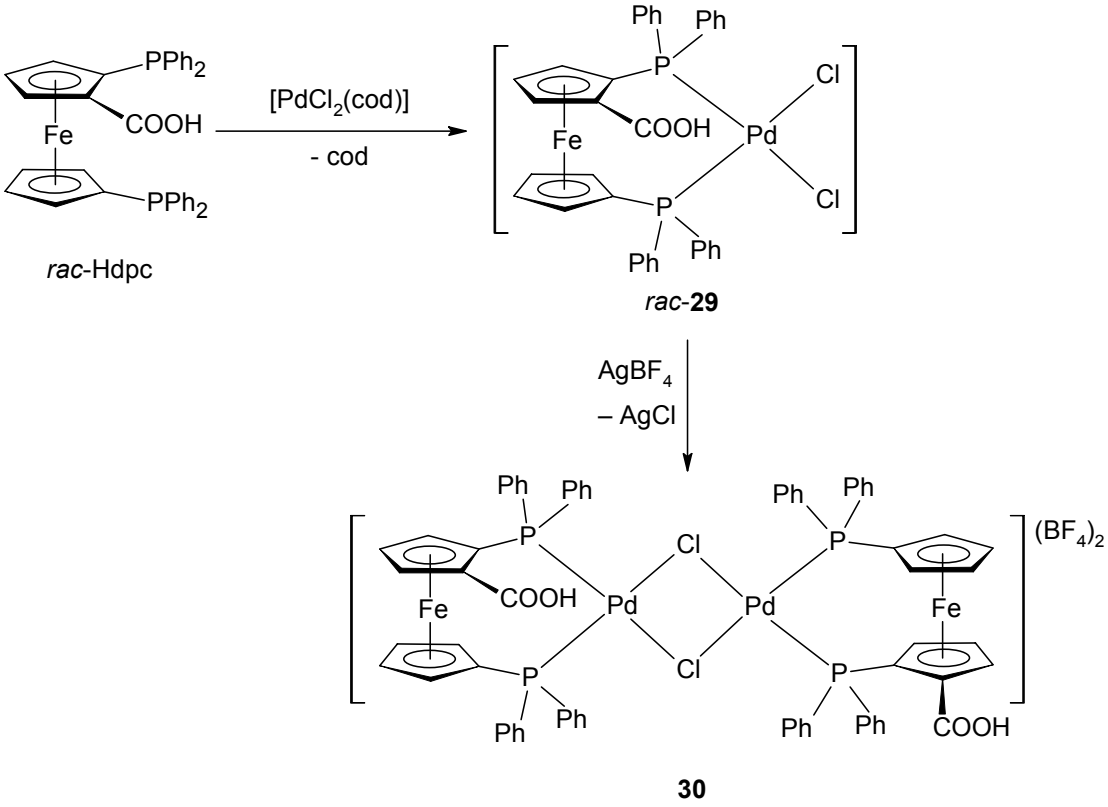


Scheme 26

The synthesis of Hdpc starts with the readily available 1,1'-dibromoferrocene (**26**), which is *ortho*-lithiated and carboxylated to yield the racemic acid **27**, as previously described by Butler and co-workers.[70] After another metalation step and subsequent phosphanylation, racemic Hdpc was obtained. Racemic acid was resolved to its enantiomers via diastereomeric esters with D-glucose diacetonide. The diastereomeric glycosides **28** were prepared by the carbodiimide-promoted coupling of the acid with

1,2:5,6-diisopropylidene-D-glucofuranose (glucose diacetonide) in the presence of 4-(dimethylamino)pyridine and separated by combined chromatography and crystallisation. Subsequently, the glycosides were hydrolysed to give the corresponding enantiomers of Hdpc. The solid-state structures of *rac*-Hdpc, the glucofuranoside (R_p)-**28**, and the methyl ester (R_p)-Medpc (resulting as a by-product during hydrolysis of the glycoside) were determined by the X-ray diffraction analysis.

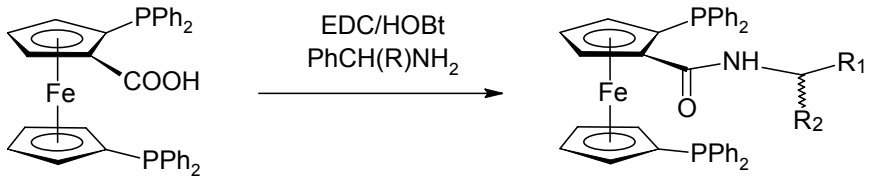
The coordination properties of racemic Hdpc were studied in palladium(II) complexes (Scheme 27). The complex *rac*-[$PdCl_2$(Hdpc-κ^2P:P')] (**29**) resulted from the reaction of *rac*-Hdpc with [$PdCl_2$(cod)], and its solid-state structure was determined. The complex also served as a precursor for the chloride-bridged dimer [(μ-Cl)$_2${Pd(Hdpc-κ^2P:P')}$_2$](BF_4)$_2$ (**30**) that was obtained upon chloride abstraction with a silver salt as a mixture of *rac*- and *meso*- isomers (in Scheme 27, the (*R*,*R*)-isomer is depicted).



Scheme 27

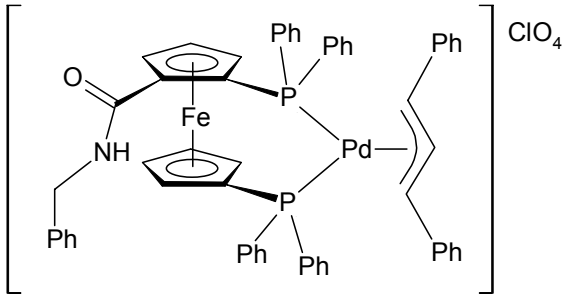
Furthermore, (R_p)-Hdpc was converted to a series of secondary amides with substituents at the amide nitrogen differing in steric properties and, optionally, also in chirality of the side chain (**31**, Scheme 28). As a model complex, possessing the

anticipated structure of the intermediate species in the course of the allylic substitution reaction, the cationic η^3-1,3-diphenylallyl complex (**32**) was prepared and its structure determined by the X-ray diffraction analysis.



(R_p)-Hdpc

R_1 = Ph, R_2 = H: (R_p)-**31a**
R_1 = Ph, R_2 = Me: (R_p,*R*)-**31b**, (R_p,*S*)-**31c**
R_1 = Me, R_2 = Me: (R_p)-**31d**
R_1 = Ph, R_2 = Ph: (R_p)-**31e**
R_1 = CH_2OH, R_2 = H: (R_p)-**31f**



32

Scheme 28

The catalytic tests (for results, see Tables 3 and 4) were performed on the above-mentioned palladium mediated asymmetric allylic alkylation of (*E*)-1,3-diphenylprop-2-en-1-yl acetate (or ethyl-(*E*)-1,3-diphenylprop-2-en-1-yl carbonate), using dimethyl (or di-*t*-butyl) malonate/base as the nucleophile, and 3 mol.-% of the catalyst formed *in situ* from the corresponding ligand and [{Pd(μ-Cl)(η^3-C_3H_5)}$_2$]. All amides of the series, as well as the parent acid Hdpc and the diastereomeric glycosides were involved in the testing, which showed only minor differences in the selectivity of the reaction caused predominantly by steric factors. The *ee* values observed for the whole series of ligands were moderate, while the highest value of 80 % was obtained with the more sterically demanding nucleophile, di-*t*-butyl malonate (for complete results, see Appendix 5). This slightly inferior performance in comparison to the amides based on the *mono*phosphanyl ligands described above can be rationalised by practically symmetric *P*,*P*-coordination of the ligands, which

does not provide sufficient electronic differentiation of the enantiotopic allylic termini such in amides that form *P*,*O*-chelates. Moreover, the amide substituent is relatively far from the coordinated metal centre and cannot effectively control the access of the nucleophile and, therefore, the selectivity of the nucleophilic attack.

Table 3 Asymmetric allylic alkylation with ligands (R_p)-Hdpc, 28, 31 (For details see Apendix 5)[a]

entry	ligand	ee (%) [config]
1	(R_p)-Hdpc	+54 [*R*]
2	(R_p)-**28**	+65 [*R*]
3	(S_p)-**28**	–60 [*S*]
4	(R_p)-**31a**	+60 [*R*]
5	(R_p)-**31b**	+55 [*R*]
6	(*R*,R_p)-**31c**	+67 [*R*]
7	(*S*,R_p)-**31d**	+60 [*R*]
8	(R_p)-**31e**	+58 [*R*]
9	(R_p)-**31f**	+58 [*R*]
10	Complex[b]	+49 [*R*]

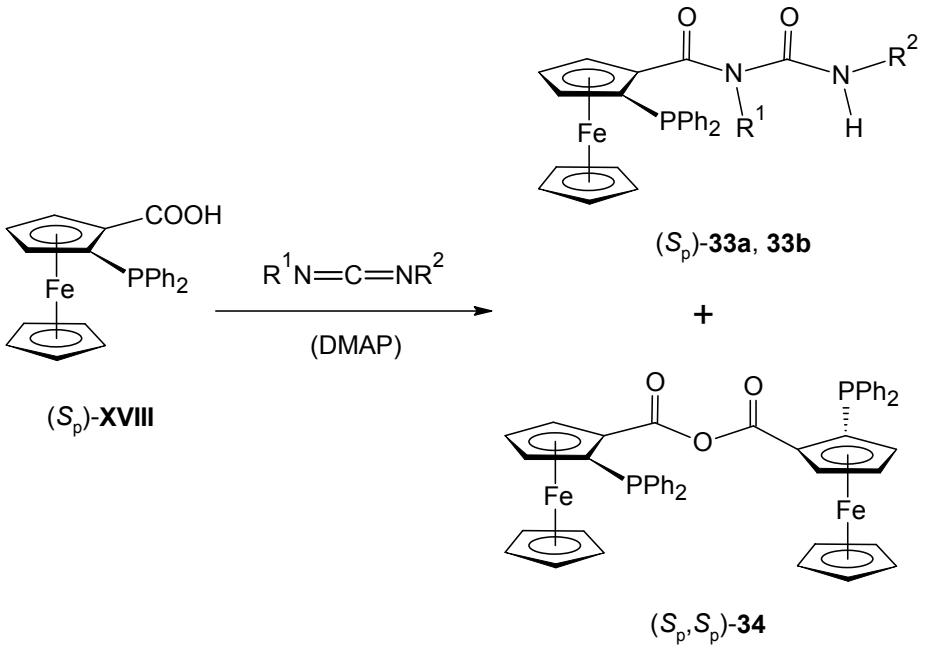
[a] Complete conversions observed in all cases after 20 h.
[b] The reaction was performed in the presence of the complex (R_p)-**32**.

Table 4 Optimalisation of the reaction conditions with ligand (*S*,R_p)-31[a]

entry	*T* (°C)	base	ee (%) [config]
1	22	LiOAc	+52 [*R*]
2	22	NaOAc	+67 [*R*]
3	22	KOAc	+66 [*R*]
4	22	RbOAc	+68 [*R*]
5	22	CsOAc	+68 [*R*]
6	22	none	+57 [*R*]
7	0	NaOAc	+67 [*R*]
8[b]	22	NaOAc	+65 [*R*]
9[c]	22	NaOAc	+80 [*R*]

[a] The conversions were quantitative with the exception of entry 9 (93 %).
[b] The reaction was performed with ethyl-(*E*)-1,3-diphenylprop-2-en-1-yl carbonate.
[c] The reaction was performed with di-*t*-butyl malonate as the nucleophile.

As an additional contribution to the topic, the reactivity in systems phosphanyl-carboxylic acid/carbodiimide was explored (Appendix 6). The experiments were prompted by the frequent utilisation of the carbodiimide-promoted coupling of carboxylic acids with alcohols and amines to afford esters or amides, respectively, during the previous work. As the studied subject, (S_p)-2-(diphenylphosphanyl)ferrocenecarboxylic acid ((S_p)-**XVIII**) and two commonly used carbodiimides: *N*-ethyl-*N*'-[3-(dimethylamino)propyl]carbodiimide (EDC) and *N*,*N*'-dicyclohexylcarbodiimide (DCC) were selected. It was found that the reaction in the absence of any base and nucleophile yielded predominantly the *N*-acylurea derivative (**33**, Scheme 29) for both diimides. On the other hand, in the presence of 4-(dimethylamino)pyridine (DMAP) as a base, the reaction gave preferentially the corresponding acid anhydride **34**, which was the dominating product in the case of DCC, while EDC afforded a mixture of anhydride with the urea derivative. Based on the observed results a plausible reaction mechanism was suggested, which is also in accordance with the conclusions reported previously for some related compounds.[71]



a: R^1, R^2 = Cy

b: R^1 = $(CH_2)_3NMe_2$, R^2 = Et

Scheme 29

Conclusions

Novel chiral ligands of ferrocene phosphanyl-carboxylic type were designed, prepared, and fully characterised by physical methods (NMR and IR spectroscopies, mass spectrometry, elemental analysis, and X-ray diffraction, if applicable). These hybrid ligands are equipped with phosphorus and oxygen donor atoms capable of coordination towards metals in various modes. Besides, they possess planar chirality, optionally accompanied by additional chirality centres present in the attached substituents.

The acids (R_p,*R*)-**1** and (R_p)/(S_p)-Hdpc are conveniently accessible by the described synthetic procedures in optically pure form either by the approach involving the functionalisation of a derivative bearing chiral *ortho*-directing group, or by resolution of a racemic product via temporary attachment of a chiral auxiliary and separation of the diastereoisomeric intermediates. Moreover, during attempts to prepare additional carboxyphosphane (S_p,*S*)-**2**, new synthetic pathways to chiral ferrocene derivatives were discovered, making use of diastereoselective deprotonation of the activated methylene group in planar chiral (phosphanyl)ferrocene derivatives.

Further structural modifications of the prepared acids proved feasible, providing an access to families of related donors as it was demonstrated with the series of amides bearing various *N*-substituents. Such variability of ligand structures is desirable, since it allows for tuning their properties readily, in order to match the particular application. In our case, it also provided the opportunity to compare coordination behaviour and catalytic performance of related ligands with respect to their structure. Furthermore, the reactions leading to carboxylic acid derivatives – esters and amides – utilising the carbodiimide coupling agents were investigated in order to optimise the reaction conditions and to avoid the formation of ferrocenoyl ureas as undesired side-products.

Coordination properties of the ligands were probed in complexes with palladium(II) and rhodium(I) and (III), respectively, chosen as examples of prominent transition metals applied to catalysis. The structures of prepared complexes manifested the ability of these hybrid ligands to coordinate in different modes involving either exclusively the phosphanyl group, or creating a chelate with both phosphorus, and oxygen (of the carboxyl or amide moiety) donor atoms participating in the coordination.

The study on catalytic potential of the new ligands in palladium-mediated asymmetric allylic alkylation showed that they could act as efficient chirality sources for

enantioselective reactions. The understanding of the role of particular ligand structures in the catalytic process was improved by the investigation into stereochemical aspects of the reaction mechanism. The synthesised and structurally characterised palladium(II) complexes bearing the η^3-1,3-diphenylallyl and respective (phosphanyl)ferrocene carboxamide ligands served as models for reaction intermediates. On the basis of structural data as well as NMR measurements, a plausible explanation of the stereochemical outcome in the discussed reaction was suggested. The investigation of relationships between ligand structure and catalytic properties in the series of related donors revealed the anticipated dominant role of planar chirality. The substituents attached via the amide moiety exhibited usually minor influence, attributable to steric factors. The different coordination modes of monophosphane ligands derived from acids **1** and **XVIII** (amides **23**) and, on the other hand, diphosphanes derived from Hdpc resulted obviously in different geometries of the catalytic intermediate and, therefore, also different catalytic results. In order to provide a comprehensive insight into the studied catalytic process, the influence of varying reaction conditions and the presence of different additives were taken into consideration, whereas, in some cases, a significant dependence of reaction rate and enantioselectivity on these factors was observed.

Abbreviations

Ac	acetyl
acac	acetylacetonate = 2,4-pentanedionate(1–)
bppfa	1-[1-(*N*,*N*-dimethylamino)ethyl]-1',2-bis(diphenylphosphanyl)ferrocene
n-, *t*-Bu	*n*-, *t*-butyl
BSA	*N*,*O*-bis(trimethylsilyl)acetamide
CBS	Corey, Bakshi, Shibata catalyst – see Ref.5 and Refs. cited therein
cod	1,5-cyclooctadiene
Cp	cyclopentadienyl
Cy	cyclohexyl
DCC	*N*,*N*'-dicyclohexylcarbodiimide
DMAP	4-(dimethylamino)pyridine
dpf^-	1'-(diphenylphosphanyl)ferrocenecarboxylate(1–)
dppf	1,1'-bis(diphenylphosphanyl)ferrocene
EDC	*N*-ethyl-*N*'-[3-(dimethylamino)propyl]carbodiimide
Et	ethyl
Fc	ferrocen-1-yl
fc	ferrocen-1,1'-diyl
Hdpc	1′,2-bis(diphenylphosphanyl)ferrocene-1-carboxylic acid
Hdpf	1'-(diphenylphosphanyl)ferrocenecarboxylic acid
HOBt	1-hydroxybenzotriazole
Me	methyl
Ph	phenyl
ppfa	1-[1-(*N*,*N*-dimethylamino)ethyl]-2-(diphenylphosphanyl)ferrocene
TfO^-	trifluoromethanesulfonate
TMEDA	*N*,*N*,*N*′,*N*′-tetramethylethylenediamine
THF	tetrahydrofuran

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Declaration

I declare that this thesis is my own original work except as cited in the references. The thesis has not been submitted, or is being concurrently submitted, for any other degree.

Prague, 9.10.2008

Martin Lamač

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