En Route to Multi-bridged Metallocenes

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ABSTRACT

En Route to Multi-bridged Metallocenes

The triphenylmethyl radical is known not to dimerise to hexaphenylethane but to a quinoid dimer with loss of the aromaticity of one benzene ring. As the aromaticity is more pronounced in ferrocene, a similar behaviour would not be expected for the triferrocenylmethyl system. In addition, due to the three dimensional character of ferrocene, the triferrocenylmethyl system offers the possibility of a coupling of the additional cyclopentadienyl ligands. From compounds derived from triferrocenylmethane or from the ferrocenophane system in which three ferrocenyl units are linked together by two bridging methylene groups, we expect highly interesting structural and electronic properties.

This work features our studies on the synthesis and the chemistry of the ferrocene analogues of triphenylmethane. Their synthesis and the study of their chemistry is the prime target of this project.

The use of ferrocene, 1,1'-bis(tributylstannyl)ferrocene or (*S*)-2-ferrocenyl-4-isopropyloxazoline allows the synthesis of either triferrocenylmethane derivatives bearing substitution at the bridged carbon atom, at the cyclopentadienyl rings opposite to the bridged ones or 1,2-disubstituted derivatives respectively.

Metallocenophanes are ring systems in which the metallocene units are joined by an atomic or a molecular bridge. The compound [1,1]-ferrocenophane in which two ferrocenes are linked together by two bridging methylene groups, is a very useful starting material for the synthesis of more complex metallocenophanes.

DDQ mediated oxidation to [1,1]-ferrocenophane-1,12-dione, followed by treatment with lithium cyclopentadienide in the presence of $AlCl_3$ leads to 1,12-dicyclopentadienylidene-[1,1]-ferrocenophane, advanced precursor of the desired trinuclear [1,1]-ferrocenophane derivative.

Reduction of the difulvene to the dicyclopentadienyl-dianion and metallation with $FeCl_2.2THF$ should lead to the desired molecule.

Ferrocene • Ferrocenophanes • Triferrocenylmethane • Lithiation • Palladium • Cross-Coupling • Asymmetric Catalysis • Ligand Design

ABSTRACT

Überbrückte dreikernige Metallocene: Synthese, Charakterisierung und Reaktivität dreidimensionaler Analoga des Triphenylmethyl-Systems

Die Dimerisierung des Triphenylmethyl-Radikals beschäftigt die Chemie seit dem Beginn des 20. Jahrhunderts und führt zu einem chinoiden Dimer. Einer kürzlich erschienenen Arbeit ist zu entnehmen, dass Ferrocen im Vergleich zu Benzol über eine ausgeprägtere Aromatizität verfügt. Daher sollen entsprechende Derivate von Metallocenen, zunächst des Ferrocens, hergestellt und untersucht werden. Es ist zu erwarten, dass sich deren Chemie deutlich von der des Triphenylmethyl-Systems unterscheidet.

Der Ferrocenyl-Substituent ähnelt der Phenylgruppe in vielen Eigenschaften, ist im Gegensatz zu dieser jedoch dreidimensional aufgebaut, was zu nützlichen stereochemischen Konsequenzen führt. Im Rahmen dieser Arbeit wurde die Synthese dreidimensionaler Analoga des Triphenlymethyl-Systemsuntersucht.

Ausgehend von Ferrocen, 1,1'-Bis(tributylstannyl)ferrocen und (*S*)-2-Ferrocenyl-4-isopropyloxazolin wurden einige Derivate des Triferrocenylmethans dargestellt, die sich in ihrem Substitutionsmuster (am verbrückenden Kohlenstoffatom, am gegenüberliegenden Cyclopentadienylliganden sowie im 1,2-Position) unterscheiden.

Ferrocenophane sind Ferrocen-Derivate, in denen die Cp-Liganden intramolekular durch organische oder metallorganische Gruppen verbrückt sind. Während [m]-Ferrocenophane sowie [m,m]- und [m,n]-Ferrocenophane in großer Zahl bekannt sind, war die Verbrückung von *drei* Ferrocendiyl-Einheiten durch zwei Brücken bis vor kurzem unbekannt. Das zweifach methylenverbrückte [1,1]-Ferrocenophan ist ein sehr intereressantes Edukt zur Synthese von komplexen Metallocenophanen.

Oxidation von [1,1]-Ferrocenophan mit DDQ gefolgt von einer Addition des Cyclopentadienids führt zum entsprechenden zweifachen Fulven. Die Verbindung ist der unmittelbare Vorläufer des gesuchten dreifach überbrückten Ferrocens. Nach Reduktion des Difulvens zum Dicyclopentadienyl-Dianion und Metallierung mit $FeCl_2$.2THF würde man das gewünschte Produkt erhalten.

Ferrocen • Ferrocenophane • Triferrocenylmethan • Lithiierung • Palladium • Kreuzkupplungen • Asymmetrische Katalyse • Ligandendesign

Die experimentellen Ergebnisse dieser Dissertation wurden in der Zeit von Juni 2002 bis September 2005 am Institut für Organische Chemie der Universität Hannover unter der Leitung von Herrn Prof. Dr. H. Butenschön durchgeführt.

Herrn Prof. Dr. H. Butenschön gilt mein besonderer Dank für die Überlassung des interessanten Themas, die stets freundliche Unterstützung, sowie die gute Betreuung und die vielfältigen Anregungen.

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Meiner Familie danke ich dafür, dass sie mich immer liebevoll unterstützt hat.

Nach drei Jahren Seite an Seite widme ich Dr. Rosa Sáez-Díaz diese Arbeit.

ABBREVIATIONS

$[\alpha]^{D}_{rt}$	Specific Rotation
Å	Angstrom(s)
aq.	Aqueous
APT	Attached Proton Test (in NMR spectroscopy)
Ar	Aryl
atm	Atmosphere(s)
ATR	Attenuated Total Reflection
Bn	Benzyl
br	Broad (in NMR spectroscopy)
Bu	Butyl
i-Bu	*iso*-Butyl
t-Bu	*tert*-Butyl
c	Concentration
°C	Degrees Celsius
calcd	Calculated
cat.	Catalyst
cm^{-1}	Wavenumber(s)
^{13}C NMR	^{13}C Nuclear Magnetic Resonance
CV	Cyclic Voltammetry
Cp	Cyclopentadienyl (C_5H_5)
δ	Chemical Shift (in parts per million downfield from tetramethylsilane)
DAST	Diethylaminosulfur Trifluoride
DDQ	2,3-Dichloro-5,6-dicyano-1,4-benzoquinone
d	Day(s)
d	Doublet (in NMR spectroscopy)
dd	Doublet of Doublets (in NMR spectroscopy)
dr	Diastereomeric Ratio
de	Diastereomeric Excess
decomp.	Decomposition
DEE	Diethyl Ether
ee	Enantiomeric Excess
EI	Electronic Impact (in mass spectrometry)

equiv.	Equivalent(s)
Et	Ethyl
E^0	Standard Potential
Ea,Ek	Anodic, Kathodic Potential
$E_{1/2}$	Half Potential
FAB	Fast Atom Bombardment (in mass spectrometry)
Fc	Ferrocene(s)
g	Gramm
GC	Gas Chromatography
h	hour(s)
^{1}H NMR	^{1}H Nuclear Magnetic Resonance
HPLC	High-performance Liquid Chromatography
HRMS	High-resolution Mass Spectrometry
Hz	Hertz
IR	Infrared
J	Coupling Constant (in NMR spectroscopy)
m	Multiplet (in NMR spectroscopy)
M	Molar (moles per liter)
M^+	Parent Molecular Cation (in mass spectrometry)
Me	Methyl
MHz	Megahertz
mL	Milliliter(s)
min	Minute(s)
mmol	Millimol
m.p.	Melting Point
Me_3SiCl	trimethylsilylchloride
MS	Mass Spectrometry
m / z	Mass-to-charge Ratio (in mass spectrometry)
μW	Microwave
mV	Millivolt
NMR	Nuclear Magnetic Resonance
Nu	Nucleophile
PE	Petroleum Ether
PG	Protecting Group

Ph	Phenyl
ppm	Part(s) per Million (in NMR spectroscopy)
i-Pr	Isopropyl
q	Quartet (in NMR spectroscopy)
rac	Racemic
RCM	Ring Closing Metathesis
ROMP	Ring Opening Metathesis Polymerization
s	Singlet (in NMR spectroscopy)
TBME	*tert*-Butylmethyl Ether
THF	Tetrahydrofuran
TMEDA	*N*,*N*,*N'*,*N'*-Tetramethylethane-1,2-diamine
t	Triplet (in NMR spectroscopy)
t.l.c.	Thin-layer Chromatography
TMS	Tetramethylsilane
r.t	Retention Time

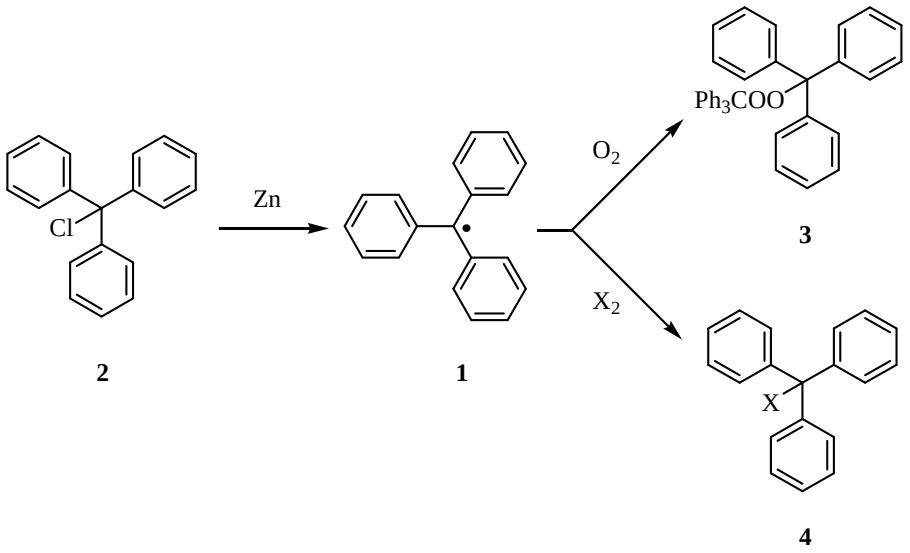
INDEX

1 Introduction

1.1 The Triphenylmethane System

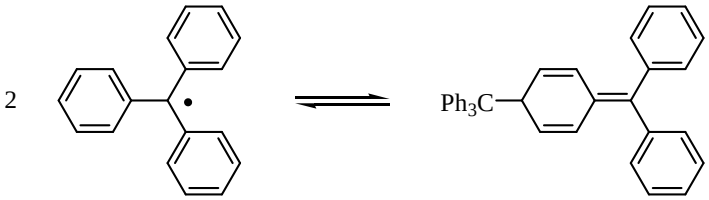
The triphenylmethyl system has attracted the interest of organic chemists since the days of Gomberg, who first postulated the existence of the triphenylmethyl radical (**1**) and the reversible equilibrium with its dimer.[1]

To Gomberg´s surprise, the reaction of triphenylmethyl chloride (**2**) with zinc did not produce hexaphenylethane but a hydrocarbon, which reacted rapidly with oxygen to give triphenylmethyl peroxide **3** and with halogens to give the triphenylmethyl halides **4**.[2]



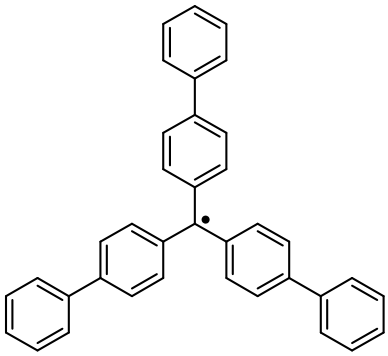
Based on colour and magnetic susceptibility measurements, the equilibrium of triphenylmethyl radical (**1**) with its dimeric form, supposed to be hexaphenylethane, was established and gone unchallenged by later investigators.[3] However Lankamp,[4] sixteen years later, conclusively demonstrated the quinoid structure **5** of the dimer* based on spectroscopic data.

* The triphenylmethyl radical (**1**) appears to be too crowded around the central *α*-carbon atom for hexaphenylethane to be formed; instead a bond is formed between the *α*-carbon atom of one radical with the less hindered *para*-carbon atom of the second radical. This process takes place at the cost of one benzene ring´s aromaticity.



1 **5**

Due to its high reactivity towards oxygen, Gomberg[5] did not isolate the triarylmethyl radical **1**, but the yellow peroxide **3**.* It was Schlenk,[6] who provided definitive evidence for the free radical concept. Schlenk prepared tris(biphenyl)methyl radical **6** and isolated it as a black crystalline compound that was almost completely dissociated in solution.



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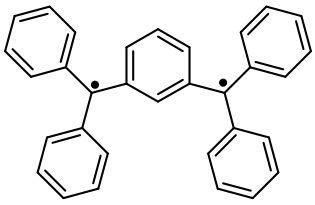
In one hand, Gomberg´s discovery, not only led to the modern theories of structure and reactivity of organic molecules, but marked the dawn of an entire new field of research which range from organic and polymer synthesis, biological and medicinal applications, to materials science.[7]

The science of free radical chemistry showed remarkable advancement during the century following Gomberg´s seminal work, and soon after, a variety of related persistent radicals were prepared. The stable diradical **7** analogous to triphenylmethyl was reported by Schlenk

* Despite this problem, Gomberg confidently proposed the formation of triarylmethyl radical, a trivalent carbon species. This concept received very strong criticism and Gomberg had to be on the defense for more than 10 years.

in 1951, marking the beginning of the study of “high-spin” molecules. These are, nowadays, gaining increasing attention because of the recent discovery of magnetic ordering in conjugated organic polymers such as **8**.

The main target in this field, is the synthesis of very “high spin” organic molecules that can act as organic magnets. In this context, is not surprising that the most promising materials are arylmethyl-based polyradicals, as triarylmethyl derivatives remain one of the best known examples of carbon centered free-radicals and the benzene building block allows efficient modular synthesis of complex networks.[8]



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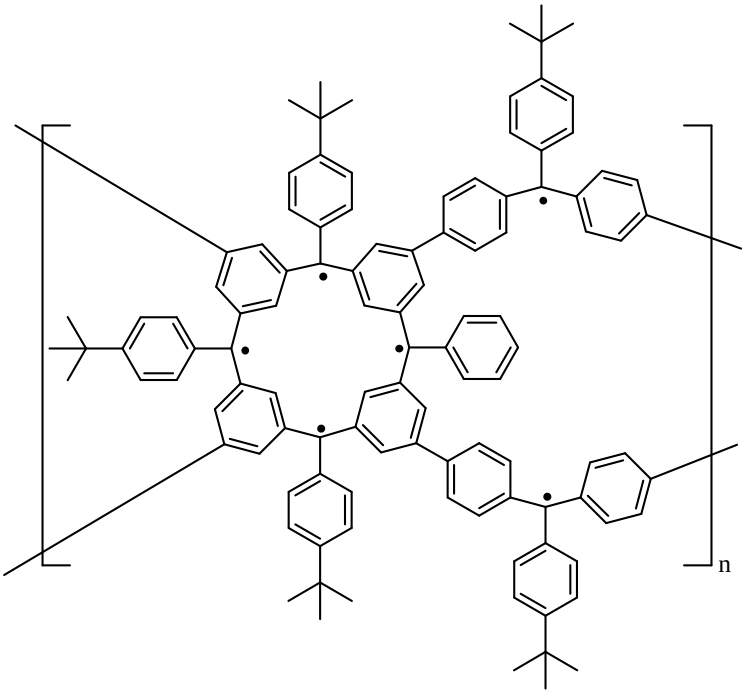

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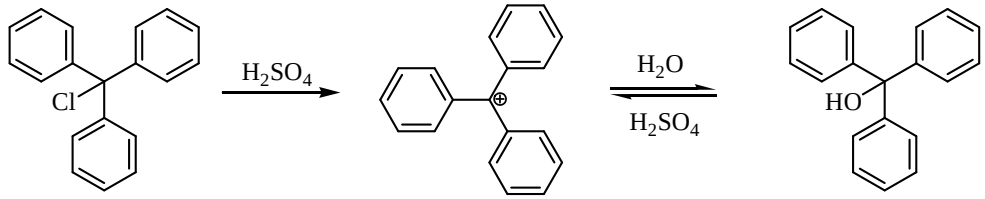
On the other hand, Gomberg´s work immediately attracted the attention of the world chemical community into the chemistry of the triphenylmethane system which turned to be a fruitful field.

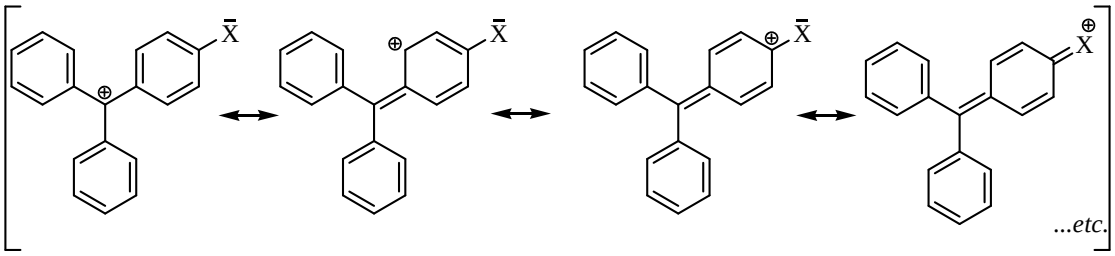
On the heels of Gomberg´s discovery, Norris´s and Kehrmann´s independent observations and reports are generally credited with the discovery of carbocations. They separately observed deep yellow solutions on the dissolution in concentrated sulfuric acid of the colourless triphenylcarbinol **9** and triphenylmethyl chloride (**2**), respectively. It was, however, Adolf Baeyer in Munich who in 1902 recognized and reported the saltlike character of this

type of compounds and the correlation between the formation of salt and the appearance of colour.[9]

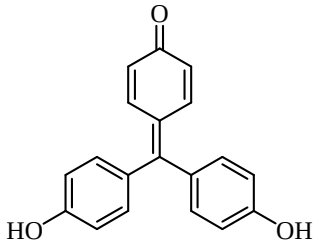


2 **10** **9**

In this context, the work of Baeyer revealed one fascinating aspect of triphenylmethane chemistry: its ability to increase the stability of carbocationic intermediates by introducing substituents that facilitate the charge delocalization in the aryl rings.

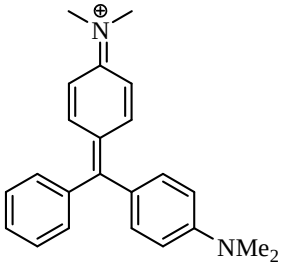


Triphenylmethyl-based carbocations, that are able to give stable quinoid forms, occupy an important niche in organic dye chemistry representing an old and numerous class of dyes and fluorophores (rosolic acid **11**, malachite green **12**, xanthene **13**, *etc*.)[10] which still find nowadays applications in many fields.[11]



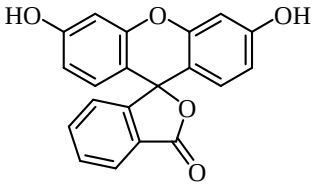
Rosolic acid

11



Malachite green

12



Xanthene

13

1.2 Ferrocene (14) Replaces Benzene (15)

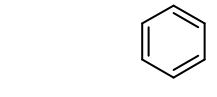
A half century after its discovery, ferrocene chemistry has developed into one of the most fruitful fields in organometallic chemistry, and still attracts a great deal of chemical interest due to its versatility in a variety of synthetic and material applications.[12] Ferrocene (**14**) combines chemical versatility with high thermal stability, and these properties, together with its exceptional electrochemical properties, make ferrocene-based complexes good candidates for the preparation of new materials with application in organic synthesis, catalysis and material science.[12]

14

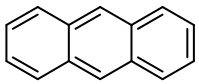
1.2.1 Ferrocene (14): More Aromatic than Benzene (15)?

Benzene (**15**), the epitome of aromaticity, was the first compound to exhibit this phenomenon.[13-15] The special properties of benzene (**15**) are usually associated to Hückel's rule which states that a cyclic conjugated ring containing [4n+2] π-electrons is particularly stable ("aromatic"). This concept has been applied to almost all cyclic conjugated compounds, however, aromaticity is not only restricted to benzene (**15**) and related cyclic, polycyclic and

heterocyclic conjugated rings but includes all monocyclic (4n+2) annulenes and dehydroannulenes.



Benzene
15

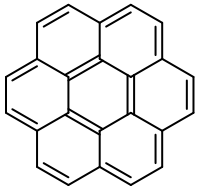


Anthracene

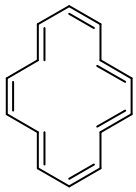
Pyridine

Furan

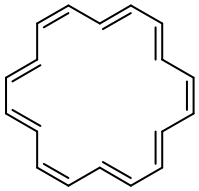
Tropylium Cation



Coronene



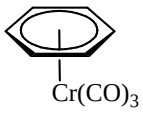
[14]-Annulene



[18]-Annulene

An interesting case is a [4n+2] moiety ligated to a metal center or to an organometallic fragment such as depicted in ferrocene (**14**) and related metallocenes (sandwich and half sandwich complexes). The question arises, whether the cyclopentadienes in ferrocene derivatives and in ferrocene (**14**) itself are aromatic and if they are, will they be more or less so than benzene (**15**)?

14



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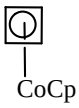


17

The synthesis and isolation of ferrocene (**14**) was first reported independently by two research groups, Kealy and Pauson[16] from Duquesene University, and Miller[17] from British Oxygen Company, in late 1951 and early 1952, respectively. This discovery marked a major milestone and turning point in the evolution of modern organometallic chemistry, and laid the foundation for the widespread development of the chemistry of ferrocene (**14**) and other metallocenes.[18]

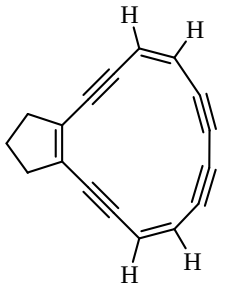
In several aspects, the cylindrical molecule of ferrocene (**14**) is analogous to the planar molecule of benzene (**15**). Its discovery was followed by numerous chemical confirmations

that it possesses an aromatic system. In this respect, ferrocene (**14**), as benzene (**15**), undergoes Friedel-Crafts acylation and alkylation, can be formylated, sulfonated, metalated with butyllithium, phenyl sodium and mercuric acetate, arylated with diazonium salts, and treated with isocyanates to produce *N*-substituted amides. However, typical aromatic-type reactions such as nitration or direct halogenation lead to destruction of the molecule, presumably through oxidation of the iron atom.[12, 19]

While there is little doubt that ferrocene (**14**) is aromatic, its degree of aromaticity is less clear. Typical indicators of aromaticity are the ring current effect on protons attached to the perimeter as measured by their ^{1}H NMR shifts[13] and quantum chemical NICS calculations.[14] In the case of ferrocene (**14**) neither of the two methods gives a good measure of its aromaticity, because both values are distorted by the influence of the sandwiched iron atom. Consequently a more remote way of measuring the aromaticity of the cyclopentadienyl rings in ferrocene (**14**) is desirable.

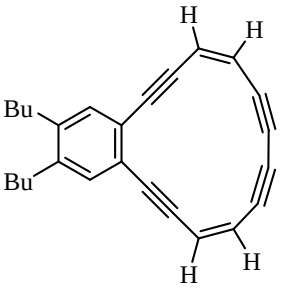
Recently Bunz[20] reported evidences of ferrocene (**14**) being more aromatic than benzene (**15**) based on experimental measurements of ferrocene-dehydro[14]annulenes. The decrease / interruption of aromaticity of the large dehydroannulene ring by an anellated aromatic moiety can be observed by a shift change in the ^{1}H NMR spectra of the vinylic protons - a major localizing power (aromaticity) of the anellated unit results in a major upfield of the vinylic protons.

This effect can be use as a sensitive prove for the measurement of the relative aromaticity. Dehydroannulenes **19** and **20** allowed Bunz to directly compare the effects of benzo- *vs.* ferrocene-anellation onto an aromatic [14]annulene.



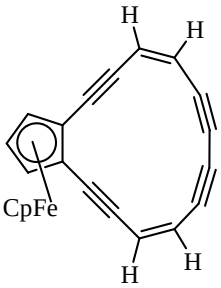
d = 7.24, 7.78 ppm
J = 9.8 Hz

18



d = 6.63, 7.33 ppm
J = 10.0 Hz

19



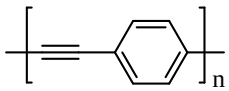
d = 6.21, 6.75 ppm
J = 10.2 Hz

20

These results point that in the ferrocene case the localizing power of the cyclopentadienyl ring is substantially larger than that of benzene (**15**): ferrocene (**14**) is more aromatic than benzene (**15**) by this measurement. However further experiments and calculations should be necessary to either reject or support this result.

1.2.2 Ferrocene (14): Three Dimensional Analogues of Wholly Organics Materials

Supramolecular systems composed of organic or metal-organic building-block units, that are connected by strong covalent bonds containing π-rigid fragments, constitute an important research area because of their potential for creating “designer materials” having tailorable electronic, optical, magnetic, catalytic and other properties.



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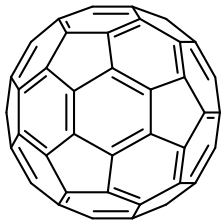

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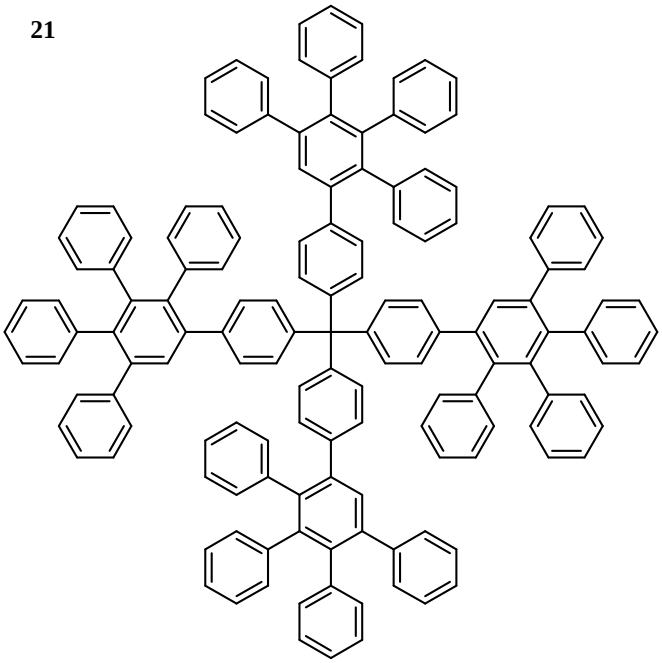


23

The benzene ring has been introduced as a modular building block into carbon-rich 1D-, 2D- and 3D-polymers. Remarkable synthetic products are functionalized poly(*para*-phenyleneethynylene)s **21** as rigid rods, giant polycyclic aromatic hydrocarbons as molecular models for allotropic forms of carbon (graphite, [60]fullerene **22**, *etc.*), and polyphenylene dendrimers **23** as shape-persistent nanoparticles.

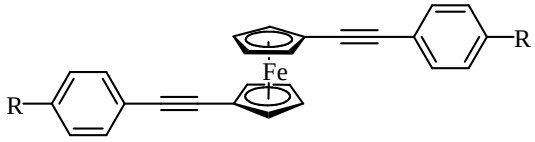
Metal-containing supramolecular systems are particularly interesting, since the metal centers may function as tunable electrophores or chromophores.[21] The replacement of one benzene (**15**) with a ferrocene (**14**) unit in macrocyclic architectures has been recognized as an attractive way to endow molecules with secondary functionalities, new geometries and new topologies as compared to the wholly organic materials.

14

15

A fundamental difference between ferrocene (**14**) and benzene (**15**) is the three dimensional structure of the organometallic compound, making it less symmetric. The X-ray crystal structure of ferrocene (**14**) revealed an iron metal sandwiched by two cyclopentadienyl (Cp) ligands, which lie in parallel planes with a separation of 330 pm; this distance is comparable to the Van der Waals thickness of an aromatic ring *e.g.*, the interplanar distance of approximately 340 pm found in crystalline arenes, so that ferrocene (**14**) can roughly be thought of as a dimer of two aromatic systems within which an iron atom is “hidden”, but still reveals its presence through the variety of properties of ferrocene (**14**). The Cp ligands are bound covalently to the iron center; however they rotate nearly freely with respect to each other (the activation barrier to this rotation is of the order of 4 - 8 kJ / mol), and the eclipsed conformation is slightly preferred over the staggered one (ring twist angle = 36°).[22]

The introduction of a metallocene unit into one-dimensional oligomers or polymers may lead to a range of properties (*e.g.* redox, optical, electrical, and catalytic) that differ from those of conventional organic polymers.



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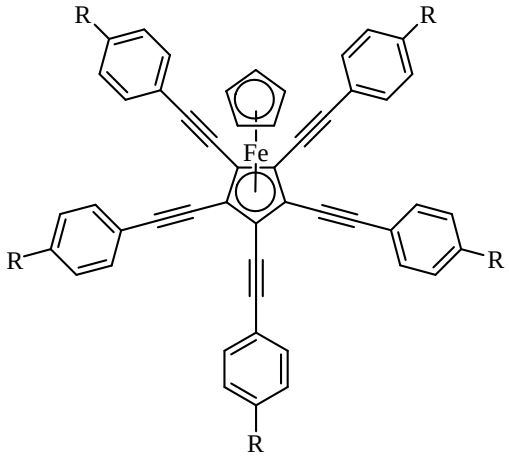
Butenschön 2003[23]

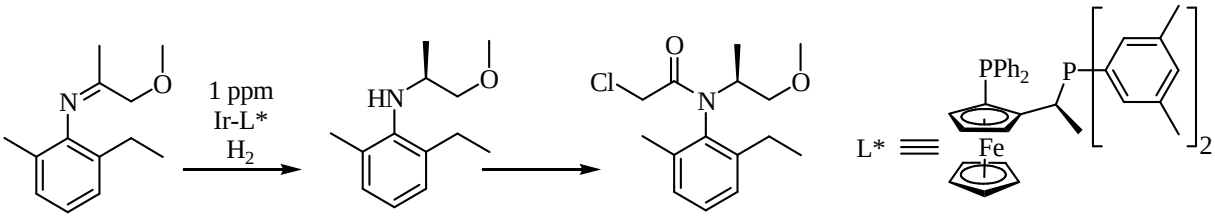


25
Bunz 2003

For example, replacement of an arene ring in poly(*para*-phenyleneethynylene)s rods **21** or in giant polycyclic aromatic hydrocarbons would make the structures three-dimensional and thereby reduce their possibility of aggregation. In addition, a ferrocene unit in wire-type compounds would lift the rigidity of such molecules **24** due to the rotation around the cyclopentadienyl-iron-cyclopentadienyl axis. So those structures can be expected to behave like foldable rulers, which can adjust their effective length as required.[23]

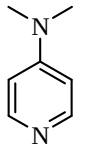
1.2.3 Planar Chirality

The three dimensional character of ferrocene (**14**) makes it different from benzene (**15**) with respect to the stereochemistry: a derivative with at least two different substituents in the same ring cannot be superimposed with its mirror image, is planar chiral, a special case of chirality in which a molecule does not possess an asymmetric carbon atom but perpendicular dissymmetric planes. Planar chirality plays a significant role in many asymmetric catalytic processes and is often implemented by the application of metallocenes such as ferrocene derivatives in industrially important syntheses. One example is the preparation of the herbicide (*S*)-metolachlor (**28**), which is obtained by an asymmetric hydrogenation reaction mediated by ferrocenyldiphosphane **29**.[24]



26 **27** **28** **29**

Moreover, it has been possible to design ferrocene derivatives of benzene systems, with higher degree of asymmetry. In this context, new planar chiral-ligands or catalysts as **30 - 32** lead to considerably improved performances or new applications.[25-27]



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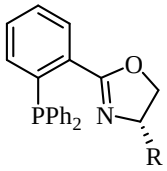

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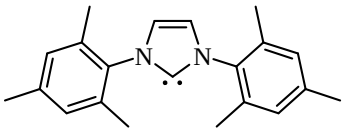
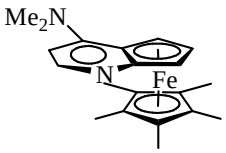


Arduengo 1999



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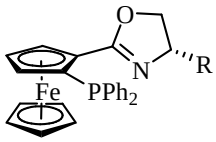
Fu 2001[25]



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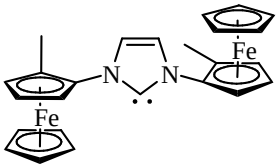

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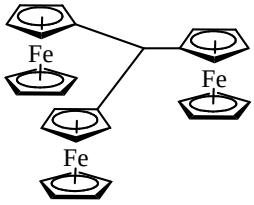
Togni 2005[26]

2 En Route to Multi-bridged Metallocenes

2.1 Aim of the Project: Ferrocene Triphenylmethane Based Analogues

Based on ferrocene (**14**) two different analogues of the triphenylmethane system can be envisaged, the known triferrocenylmethane (**33**)[28] and the ferrocenophane system **34** in which three ferrocenyl units are linked together by two bridging methylene groups.



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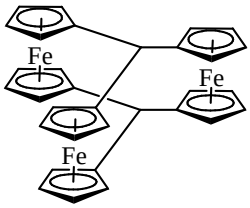


34

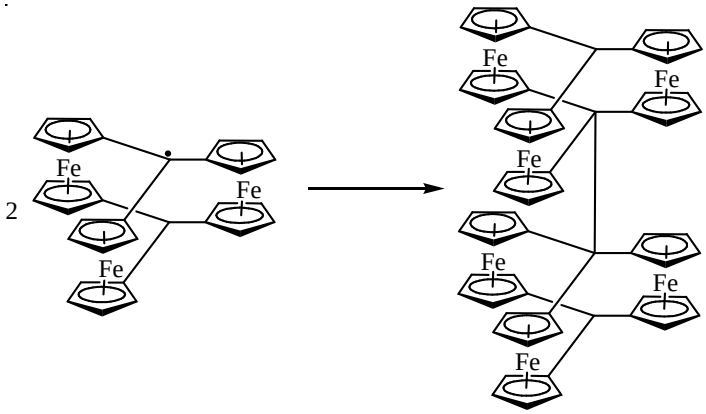
The different structural features of these two compounds are expected to confer to these molecules markedly different chemical and physical properties.

In the flexible triferrocenylmethane (**33**), the steric repulsion between the three ferrocenyl substituents is expected to force the molecule to take the less steric-strained conformation around the central carbon atom. In contrast, the two methylene bridges in **34** are expected to eliminate the free rotation of each ferrocenyl unit, fixing them in a mutually coplanar geometry.

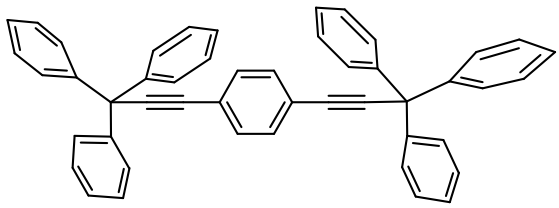
Concerning the role of the two methylene bridges in **34**, there will rise a question about the integrity of this molecule. The central atom, although "sp^3" hybridized (tetrahedral) will be forced to adopt a pyramidal conformation. If so, trivalent species, with "sp^2" (planar) can be expected to be more stable (charged carbocation, neutral free radical and negatively charged carbanion).

It is our thought that a comparison of triphenylmethane and ferrocene based analogues **33** or **34** is of interest with respect to the chemistry at the *quasi*-benzylic carbon atom. Particularly interesting should be the influence of the metallic moieties in the stability of trivalent species [as the electronic and structural properties of ferrocene (**14**) should make them more stable as compared to the aryl-based compound].

Furthermore, the “carousel type structure” **34** has a potential as a building block in supramolecular chemistry; if it were possible to fix two of these molecules through a covalent bond (*e.g*. with the help of a radical dimerization), then the rotation of the triferrocenyl fragment around the carbon-carbon bond axis could be expected. In which case, it would be worth investigating whether the rotation of such molecule could be controlled in a planned way or not.

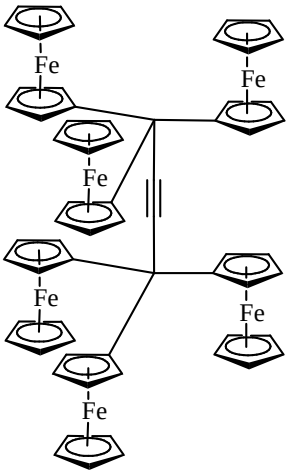


One of several well explored molecular architectures for the synthesis of molecular compasses and gyroscopes is based on 1,4-bis(triarylpropynyl)-benzenes **35**.



35

A ferrocene derivative of **35**, might be designed based on the triferrocenylmethane system. This way, it could be possible to construct the analogous systems **36** - **38**, with interesting macromolecular properties. Mandatory is then, to develop a robust and facile method for the substitution at the bridge carbon atom in the triferrocenylmethane system.



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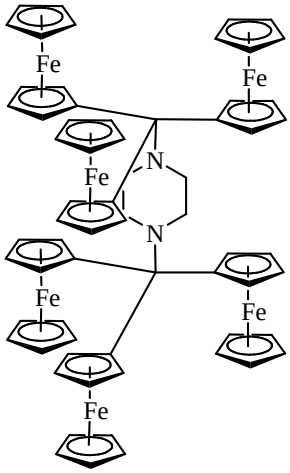

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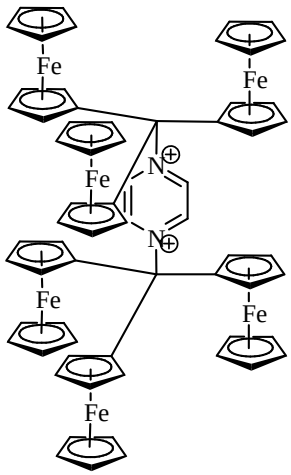

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With the intention to werge the chemistry of trimetallic three-dimensional derivatives of the triphenylmethane system, the objective of this investigation is the synthesis of the unknown ferrocenophane **34** and the study of the chemistry of the known triferrocenylmethane (**33**).

From compounds derived from **33** or **34** we expect highly interesting structural and electronic properties. Their synthesis and the study of their three dimensional architecture is the prime target of this project.

3 Results and Discussion

3.1 Metallocenes

The discovery by Pauson and Miller[17] in the early 1950's of "a new type of organo-iron compound" [ferrocene (**14**)] has attracted a great deal of research effort on the study of bis(η^5-cyclopentadienyl)metal sandwich complexes (metallocenes).[12]

One of the scientifically rich areas of metallocene study has been that of linked metallocenes. Organic modifications of cyclopentadienyl-type ligands or of metallocenes themselves have permitted to scientists the construction of a range of molecules comprising more than one metallocene unit or numerous modes of ring attachment.

The presence of two or more metal centers within the same molecule profoundly affects both the physical properties and the reactivity of the molecule. It either results in a significant modification of the individual properties or in the development of novel characteristics which do not occur in monometallic compounds.

Moreover, in polymetallic complexes, the reciprocal interaction between the active centers can be observed by the effect of chemical, electrochemical, or photochemical modifications of one metallic center on the properties of the other. Even though the metal atoms in these systems do not lie in intimate contact, electronic communication[29, 30] between them is possible either as through-bond effects, through-space effects or perhaps a combination of both.*

A number of potential applications for metallocene systems with this type of 'electronic communication may be envisaged: as electrode mediators, precursors to magnetic solids, charge transport materials and components of electronic devices or sensors.[12, 30, 31]

* When one electron is removed from a molecule with two (or more) M^{II} metallocene centers, two extreme situations may be envisaged: either a mixed-valence cation with distinct localized M^{II} and M^{III} sites, or a completely delocalized cation with two equivalent metals, each in oxidation state 2.5+. These extremes correspond to classes I and IIIA respectively in Robin and Day's classification of mixed-valence species. Class I compounds show no metal-metal interaction: their properties are the sum of those of the component metallocene and metallocenium units. Class IIIA compounds feature strong metal-metal interactions; the properties of the component species are replaced by those of a new delocalized species. Between these two extremes lies a wide range of intermediate cases with many graduations of metal-metal interactions.

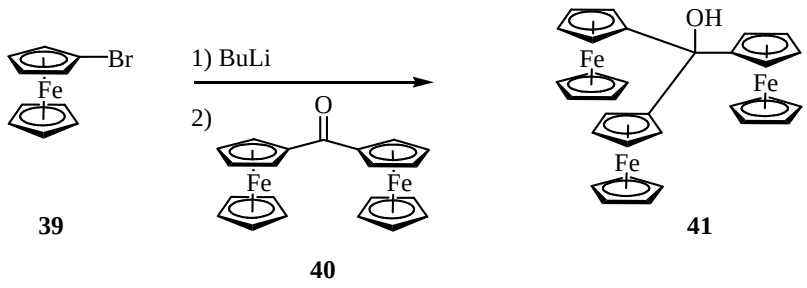
The great interest for transition metal complexes does not only arise from the aforementioned particularities but also from the wide range of arrangements, which can be created due to the huge flexibility of the organometallic structures.

3.2 Bridged Ferrocenes

Much attention has lately been devoted to the chemistry of ferrocene complexes, because ferrocene (**14**) combines chemical versatility with high thermal stability. These properties, together with its exceptional electrochemical properties, make ferrocene-based complexes good candidates for the preparation of new materials with applications in organic synthesis, catalysis and material science.[12]

The construction of molecules comprised of more than one metallocene unit has focused in the chemistry of iron species for a great variety of reasons: ease of organic functionalization of ferrocene (**14**), chemical stability of ferrocene (**14**) and ferrocenium species, and diamagnetism of neutral ferrocene (**14**) enabling characterization by nuclear magnetic resonance. Indeed, many of the desirable characteristics of the parent ferrocene (**14**) are retained in the bridged systems, leading to useful applications.[12]

Derivatives of ferrocene (**14**), in which the cyclopentadienyl rings are connected by all carbon bridges have attracted much research interest.[29, 30] Although a wide range of molecular structures containing more than one ferrocene unit have been described, triferrocenylmethyl derivates have been investigated little so far, and this is most likely because of the difficulties encountered in the synthesis of the triferrocenylmethyl scaffold. Triferrocenylmethanol (**41**) has been synthesised by Pauson and Watts[28] by the addition of ferrocenyllithium to diferrocenylketone (**40**). The stumbling block in this sequence actually is the availability of the starting materials rather than their conversion to triferrocenylmethanol (**41**).



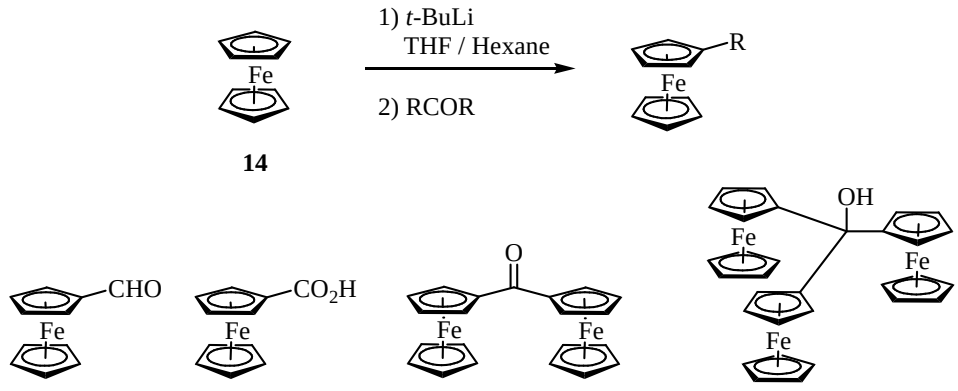
39 **40** **41**

Due to our interest in trimetallic metallocenes, we sought a method of synthesis that directly utilised commercially available ferrocene (**14**) as starting material.

Many synthetic methods for the introduction of the ferrocenyl moiety into a wide range of molecular structures have been described, mostly electrophilic substitutions or reactions involving metallation as a first step.[12]

Monolithioferrocene is a key reagent in the preparation of substituted ferrocenes. Unfortunately, BuLi metallates ferrocene (**14**) to give a mixture of both mono- and 1,1´-dilithioferrocene under almost any condition. Kagan found that the best compromise is the system *t*-BuLi / THF / hexane at 0 °C, giving around 70 – 80 % of monolithioferrocene [however, mixed with some 1,1´-dilithioferrocene and ferrocene (**14**)].[32]

The reaction of organolithium compounds with an appropriate carbonyl acceptor has long been known in the repertoire of organic synthesis as a reliable method for the preparation of carbinols, aldehydes, ketones, amides, esters and carboxylic acids. Addition of the appropriate carbonyl compound (ethyl chloroformate, carbamoyl chloride, CO_2 or DMF) to an excess of monometallated ferrocene allows the straightforward synthesis of triferrocenylmethanol (**41**),[28] diferrocenylketone (**40**),[28] ferrocenecarboxylic acid (**43**),[33] and ferrocenecarbaldehyde (**42**).[32]

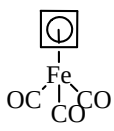


14

42[32] (61 %) **43**[33] (54 %) **40**[28] (38 %) **41**[28] (63 %)

3.3 Triferrocenylalkane Derivatives

The stabilization of carbocationic sites by neighbouring π-ligand complexes of transition metal centers has been achieved with a wide range of organometallic fragments, including (cyclobutadiene)tricarbonyliron (**44**),[34] (arene)tricarbonyl chromium (**45**),[35] (cyclopentadienyl)(tetraphenylcyclobutadiene)cobalt (**46**),[36] *etc*.



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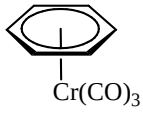

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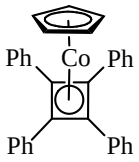

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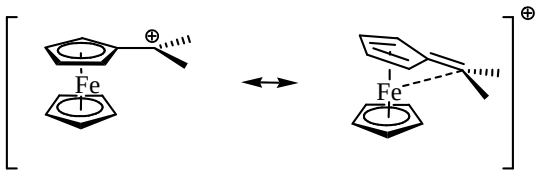
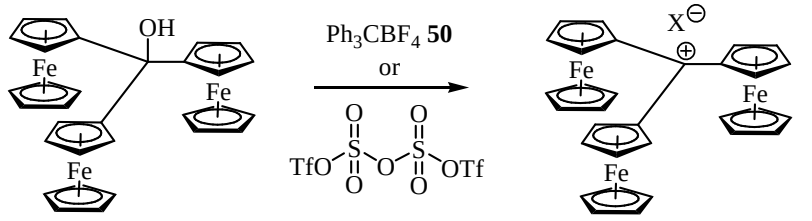
Noteworthy is the unusual stability of α-ferrocenylalkylcarbenium ions **47**. Their electronic and geometrical structural features, as well as their chemical and stereochemical behaviour have been active topics of scientific research. After much early controversy, it is now generally agreed that the stabilization is the result of a direct interaction of the iron atom with the carbocationic center, leading to a geometrical change to approach the charged carbon atom to the metal. An extreme view would regard such complexes as being comprised of a neutral fulvene ligand coordinated in a η^6-fashion to a $(C_5H_5)Fe^+$ moiety.[37, 38]



47

As one consequence, α-ferrocenylalkylcarbenium ions **47** are so stable that they form quantitatively from appropriate precursors (*e.g.* alcohols) on dehydrative treatment with acid and many of them remain unchanged in solution for several days.[39, 40]

Alternatively, we found that triferrocenylcarbenium salts **48** and **49** can be readily accomplished by alcohol abstraction with triphenylmethylcarbenium tetrafluoroborate (**50**)*[1] or on treatment with trifluoromethane sulfonic anhydride, respectively.



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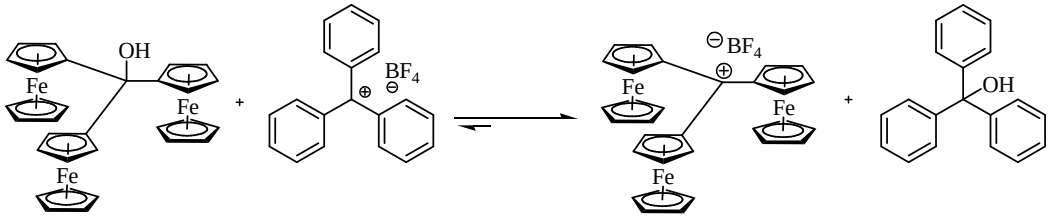
48 X = BF_4 (87 %)
49 OTf (96 %)

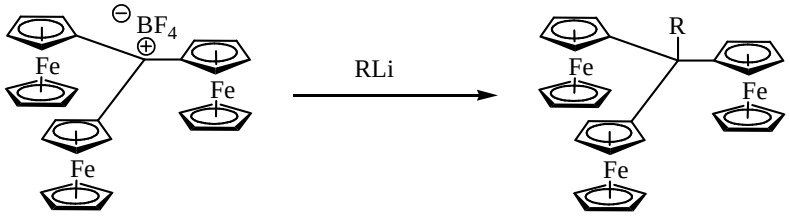
Pure **48** was treated with a number of nucleophiles to give some known as well as some unknown derivatives of triferrocenylmethane (**33**). The reaction with lithium aluminum hydride gave the parent compound triferrocenylmethane (**33**).[41, 42] The reaction with methyllithium afforded 1,1,1-triferrocenylethane (**51**).[42] Treating **48** with *sec*-butyllithium resulted in *rac*-1,1,1-triferrocenyl-2-methylbutane (**52**), and the reaction with butyllithium gave 1,1,1-triferrocenylpentane (**53**).[42] 1,1,1-Triferrocenyl-2,2-dimethylpropane (**54**)[42] was obtained by treatment of **48** with *tert*-butyllithium.*[2]

*[1] The driving force in this reaction is supposed to be the increase of stability of the cation **48** compared to triphenylmethylcarbenium tetrafluoroborate (**50**).



41 **50** **48** **9**

*[2] Compounds **33**, **51**, **53**, and **54** were reported between 1962 and 1973; however, the analytical data published were restricted to elemental analyses and in some cases to ^{1}H NMR spectra.[41, 42]



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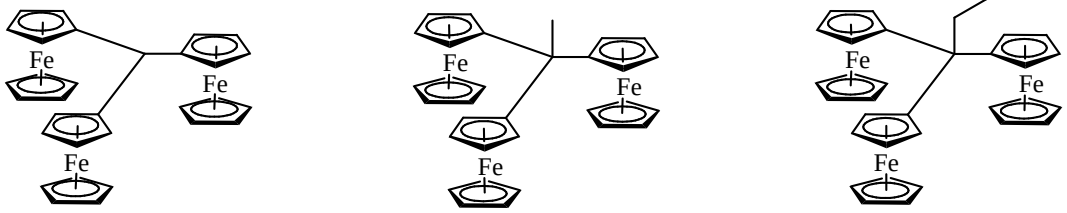
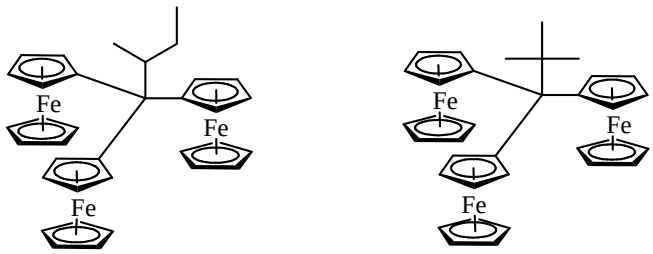


33[41, 42] (36 %) **51**[42] (28 %) **53**[42] (63 %)



rac-**52** (50 %) **54**[42] (16 %)

It was possible to crystallize the parent compound **33** from petroleum ether. The crystals obtained were suitable for an X-ray structure analysis. The analysis shows that **33** adopts an almost trigonal structure with all three ferrocenyl substitutents having cyclopentadienyl ligands whose π systems are essentially perpendicular to the *quasi*-benzylic C-H bond. Triferrocenylmethane (**33**) is the least sterically hindered representative of this class of compounds, and the ferrocenyl substituents point away from one another thereby minimizing their steric interaction.

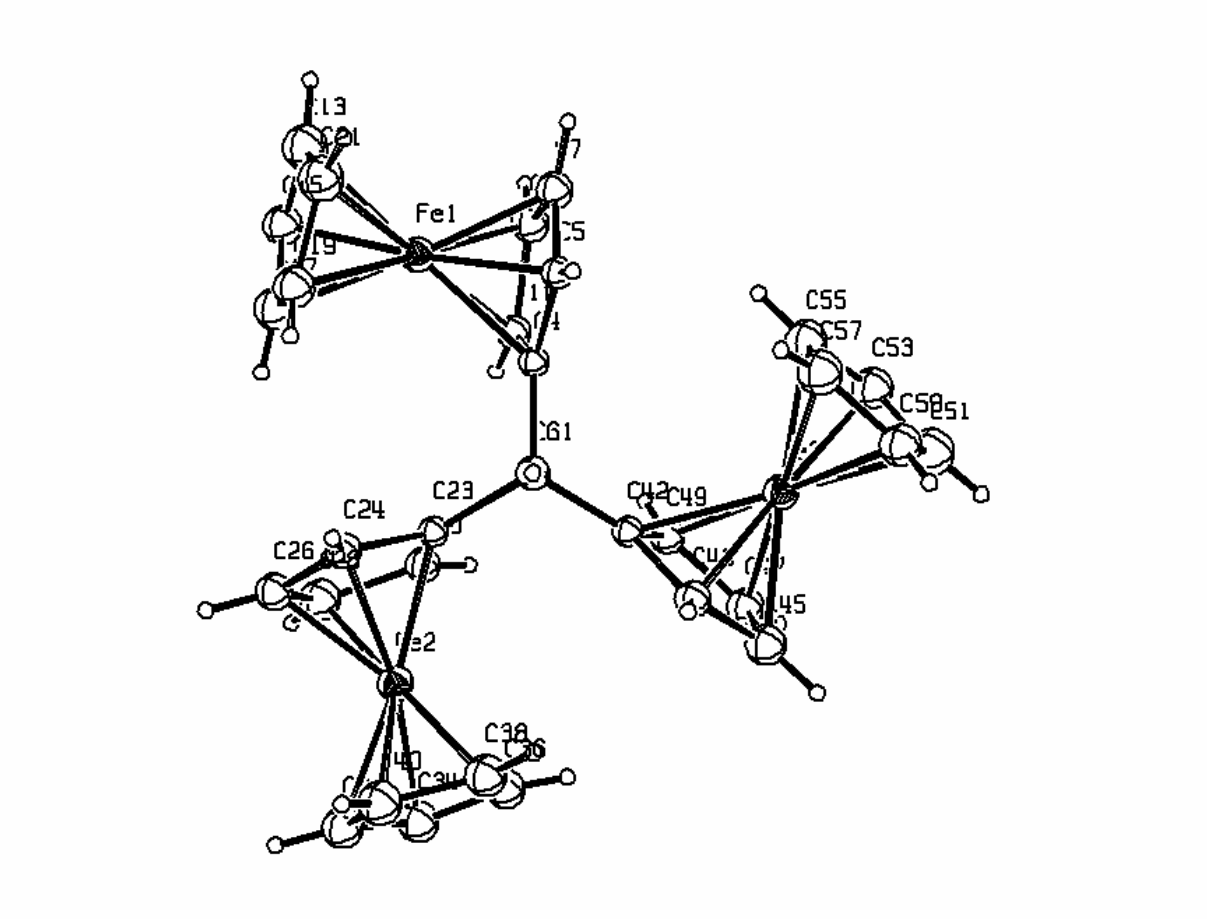


Fig. 1: ORTEP drawing of the structure of triferrocenylmethane (**33**) in the crystal. Selected bond lengths [Å], angles [°] and dihedral angles [°]: C1-C31 1.521(13), C11-C31 1.580(13), C21-C31 1.52(2), C1-C2 1.442(13), C11-C12 1.422(12), C21-C22 1.447(13), C2-C3 1.379(13), C12-C13 1.408(14), C22-C23 1.45(2), C3-C4 1.35(2), C13-C14 1.36(2), C23-C24 1.36(2), C4-C5 1.48(2), C14-C15 1.456(13), C24-C25 1.406(14), C1-C5 1.395(13), C11-C15 1.366(13), C21-C25 1.439(14), Fe1-C1 2.070(10), Fe1-C2 2.034(10), Fe1-C3 1.979(12), Fe1-C4 1.974(12), Fe1-C5 2.054(12); C1-C31-C21 113.1(8), C1-C31-C11 112.9(8), C21-C31-C11 110.3(9); C2-C1-C31-C21 –103(1), C2-C1-C31-C11 131(1), C12-C11-C31-C21 134(1), C15-C11-C31-C1 79(1), C22-C21-C31-C1 132(1), C25-C21-C31-C11 76(1).

In addition, it was possible to crystallize the sterically most demanding compound in the series, *tert*-butyl derivative **54**, from benzene. With respect to the central C31-C32 bond the molecule adopts a staggered conformation for obvious steric reasons. More interestingly, the conformation of the triferrocenylmethyl unit differs from that in **33**. In 1,1,1-triferrocenyl-2,2-dimethyl-propane (**54**) the ferrocenyl (Fc) substituents show a more screwed conformation than in **33**. While one of the Fc-C31 bonds has an anti conformation, the conformation of another is almost eclipsed, and that of the third one is more gauche.

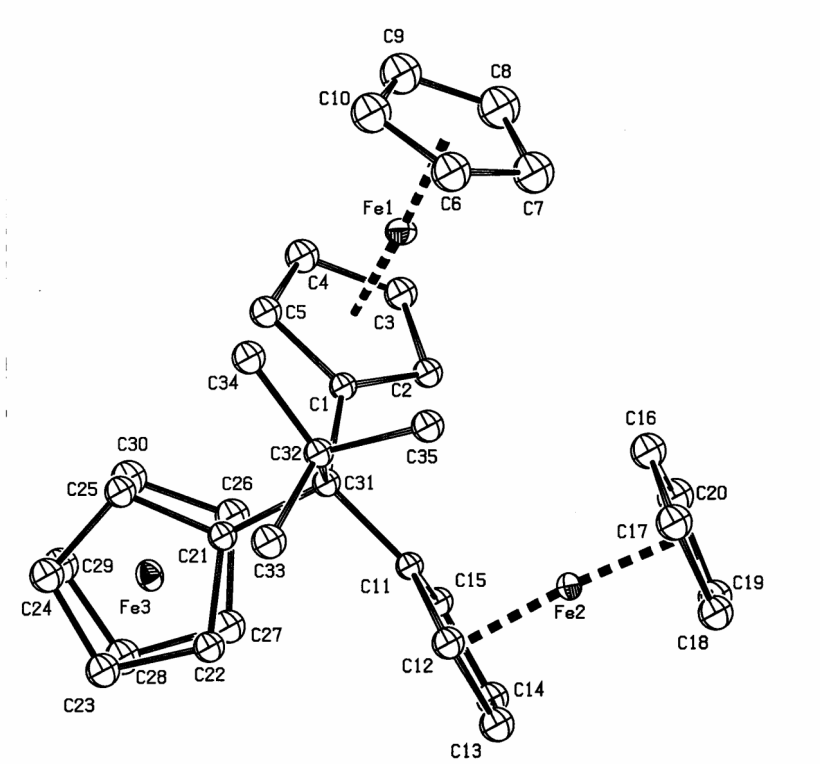
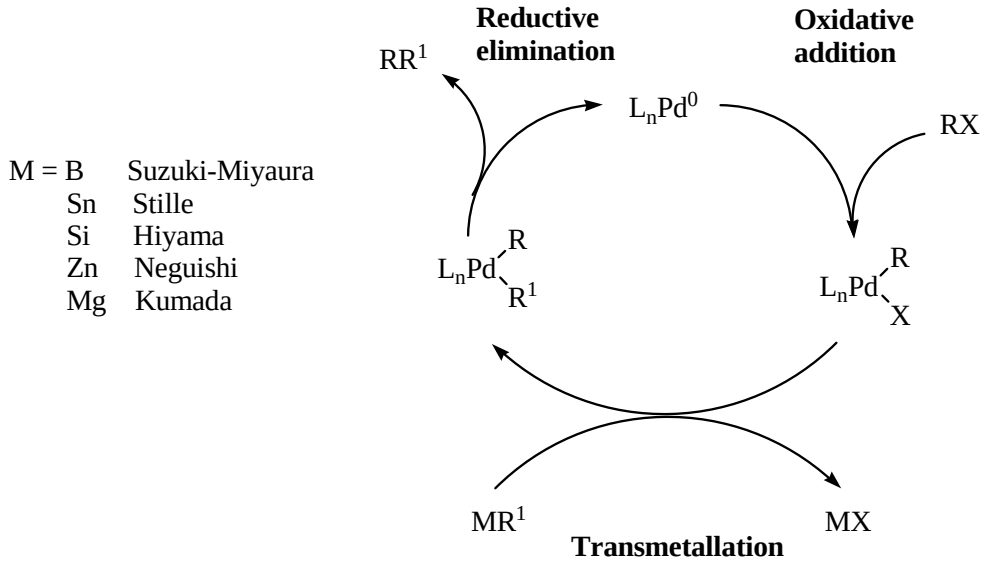


Fig. 2: ORTEP drawing of the structure of 1,1,1-triferrocenyl-2,2-dimethyl-propane (**54**) in the crystal. Selected bond lengths [Å] and angles [°]: C1-C31 1.548(4), C1-C2 1.417(4), C2-C3 1.423(4), C3-C4 1.398(5), C4-C5 1.417(5), C1-C5 1.441(4), C1-Fe1 2.159(3), C2-Fe1 2.058(3), C3-Fe1 2.016(3), C4-Fe1 2.017(3), C5-Fe1 2.052(3), C31-C32 1.606(4); C1-C31-C11 110.9(2), C1-C31-C21 108.9(2), C11-C31-C21 103.3(2); C2-C1-C31-C21 –118.6 (3), C2-C1-C31-C11 –5.5(4), C12-C11-C31-C21 –89.9(3), C15-C11-C31-C1 –47.1(4), C22-C21-C31-C1 136.7(3), C25-C21-C31-C11 –173.0(3), C1-C31-C32-C33 162.2(3), C11-C31-C32-C34 171.1(3), C21-C31-C32-C35 164.9(3).

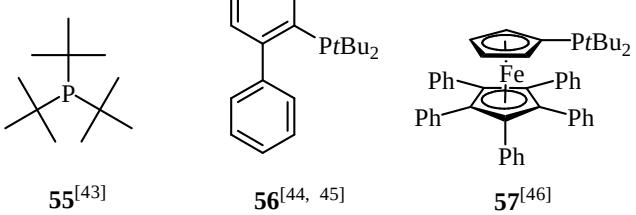
The differences in the crystal structures of **33** and **54** let us conclude that a sterically bulky substituent at the central *quasi*-benzylic carbon atom induces conformational changes, which bring the unsubstituted cyclopentadienyl ligands closer to one another.

3.4 Heteroatomic Triferrocenylmethane Derivatives

The palladium(0)-catalyzed coupling of aryl and alkenyl halides and triflates with main group organometallics via oxidative addition / transmetallation / reductive elimination sequences, has been recognized as a straightforward and powerful method for the formation of sp^2-sp^2 carbon-carbon bonds.



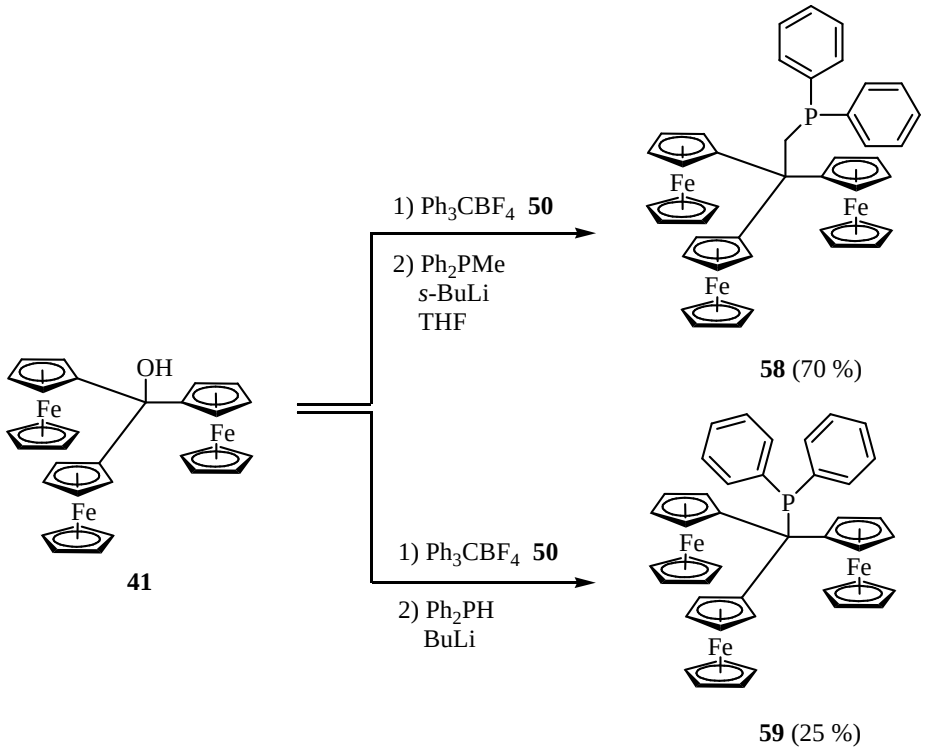
Electron-rich and bulky monodentate phosphine ligands have recently been widely applied in palladium(0) catalyzed processes. Most attention has focused on tri-*tert*-butylphosphine (**55**),[43] dialkylarylphosphines as **56**[44, 45] and pentaarylferrocenylphosphines as **57**,[46] since they have been demonstrated as unique, highly efficient ligands for a large number of transition metal catalyzed transformations: C-C coupling reactions (Suzuki-Miyaura, Heck, Stille, Sonogashira, Negishi and enolate coupling) and C-O and C-N bond formation reactions.[47]



55[43] **56**[44, 45] **57**[46]

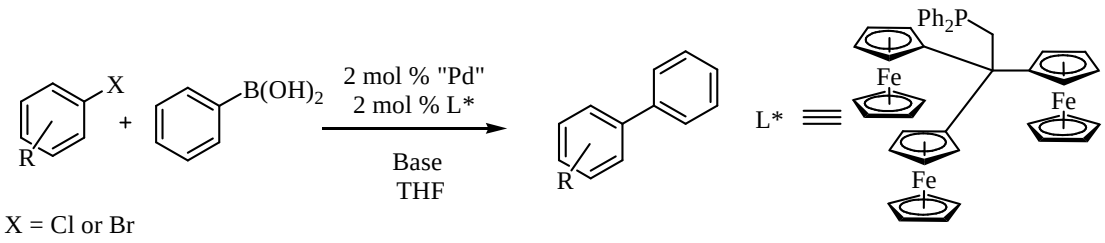
It has been proposed that the electron-richness of these ligands might favour the oxidative addition of the aryl halide bond whereas their steric demand might facilitate the ligand dissociation to give the catalytically active [Pd(0)L] species.[48] Therefore, it is of major interest to develop new bulky electron-rich monophosphines.

Phosphines **58** and **59** were prepared following the aforementioned method for the synthesis of triferrocenylmethane derivates [nucleophilic addition to triferrocenylmethyl tetrafluoroborat (**48**)]. It was reasoned that the incorporation of the triferrocenylmethane unit into the ligand backbone might lead to an enhance of reactivity due to the steric bulk of the organometallic fragment.



Subsequently, phosphine **58** was tested in the Suzuki-Miyaura reaction* between arylboronic acid and electron-poor and -rich arylhalides.

* Among palladium(0) catalyzed cross-coupling processes, the Suzuki-Miyaura reaction has become one of the most widely utilised method as it proceeds under mild reaction conditions, is largely unaffected by the presence of water, tolerates a broad range of functionality, yields non-toxic byproducts and uses arylboronic acid derivatives which are commercial available.



58

Entry	Aryl halide	Pd source	Base	Time[h]	Yield[a] [%]
1	C_6H_5Br	$Pd(OAc)_2$	$CsCO_3$	24	30
2	C_6H_5Br	$Pd(OAc)_2$	KF	24	40
3	C_6H_5Br	$Pd(dba)_2$	KF	19	54
4	4-CNC_6H_4Br	$Pd(dba)_2$	KF	19	95.5
5	4-$NO_2C_6H_4Br$	$Pd(dba)_2$	KF	72	97
6	4-CNC_6H_4Cl	$Pd(dba)_2$	KF	72	92
7[b]	4-CNC_6H_4Cl	$Pd(dba)_2$	KF	1	95
8[b]	4-MeC_6H_4Br	$Pd(dba)_2$	KF	1	52
9	4-MeC_6H_4Br	$Pd(dba)_2$	KF	24	13
10[b]	2-MeC_6H_4Br	$Pd(dba)_2$	KF	1	77
11[b]	4-$MeOC_6H_4Br$	$Pd(dba)_2$	KF	1	88
12[b]	2-BrNaphtalene	$Pd(dba)_2$	KF	1	62

a) isolated yield in %. b) μW: 250W, 150 °C, 8 bar.

Table 1. Pd(0)-Catalyzed Suzuki-Miyaura Cross-Coupling Reaction of Aryl Halides with Phenylboronic Acid.

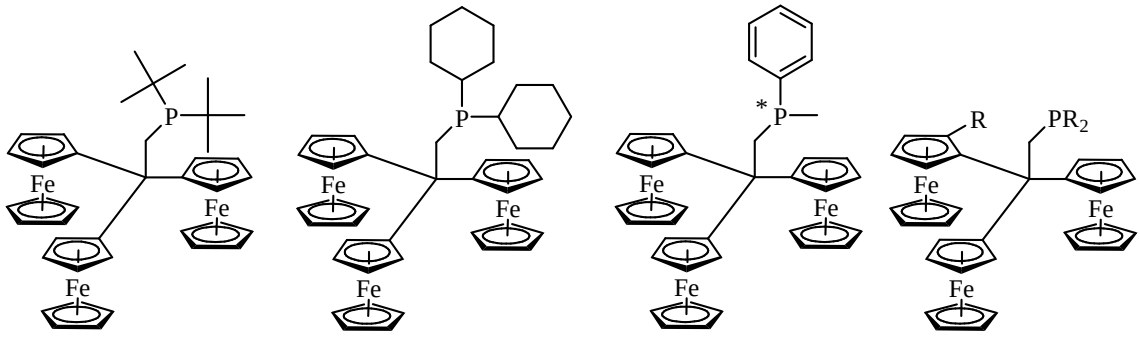
As summarized in the **Table 1**, the catalyst composed of $Pd(dba)_2$ / **58** smoothly promotes the cross-coupling reaction between electron-poor arylbromides and arylchlorides with phenylboronic acid (Entries 1 - 6). Nevertheless, electron-rich arylbromides lead to an extremely slow reaction (Entry 9).

Microwave heating has emerged as a powerful technique to assist a variety of chemical transformations such as additions, cycloadditions, substitutions, eliminations *etc*. Many examples of the benefits of microwave irradiation in palladium catalyzed cross-coupling reactions have been reported.[49] Accordingly, under microwave irradiation, $Pd(dba)_2$ / **58** cleanly effected the Suzuki-Miyaura cross-coupling of electron-rich arylbromides with phenylboronic acid in good yield (Entries 7 - 12).

There are a large number of parameters in a Suzuki reaction - palladium source, ligand, additive, solvent, temperature, ratio Pd / L, *etc*. - and there are correspondingly, a large number of protocols for accomplishing the transformation. Among them, relatively few examples occur at room temperature and most of them involve the use of dialkyl or trialkylmonophosphines as ligands.

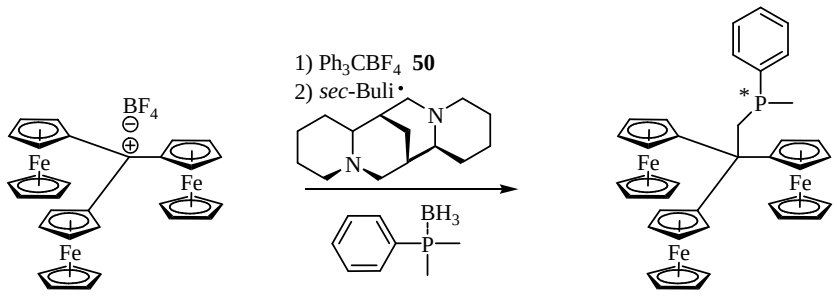
We have employed **58** which is obviously less electron-rich than a trialkyl monophosphine as **55**. Therefore it can be expected that dialkyltriferrocenylmethylphosphines **60** or **61** (much more electron-rich) will improve the performance of the catalytic system.

Furthermore, chiral phosphanes **62** and **63***[50] might be also easily accessible using the previously developed method for the synthesis of triferrocenylmethane derivatives.



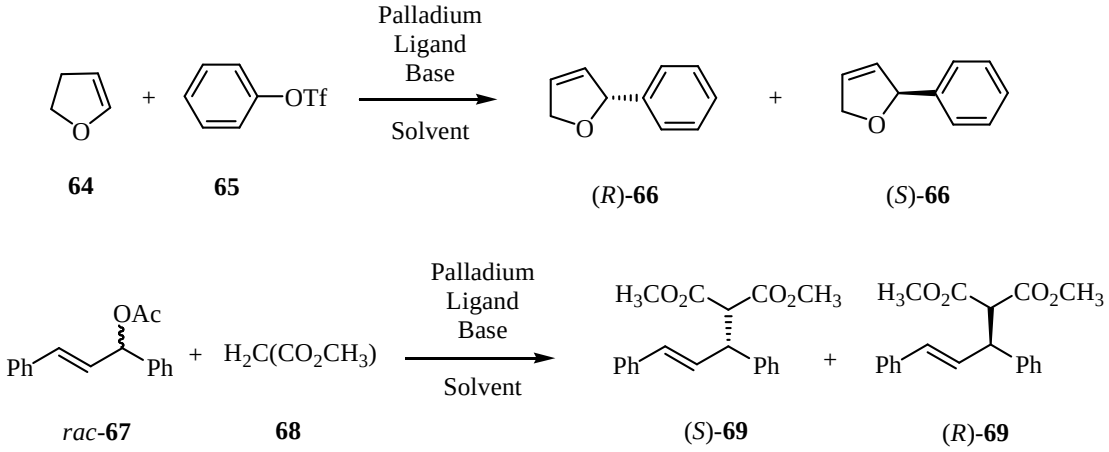
60 **61** **62** **63**

* Enantioselective deprotonation of dimethylphenylphosphane borane complex mediated by a sparteine-*sec*-BuLi complex followed by addition to triferrocenylmethyl tetrafluoroborate (**48**).[50]



48 **62**

These valuable chiral monophosphanes might be exploited in asymmetric transformations such as the intermolecular Heck reaction between dihydrofuran **64** and phenyltriflate **65** or the allylic alkylation of *rac*-1,3-diphenyl-2-propenyl acetate (**67**).



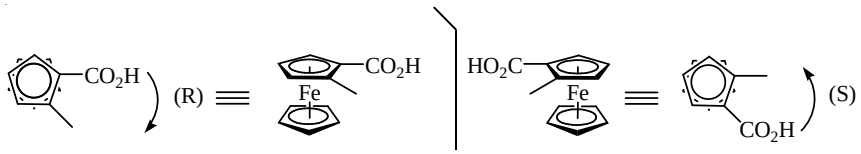
3.5 Chiral Ferrocene Derivatives

Chiral ferrocene derivatives have attracted tremendous interest during the last two decades. Among them, those exhibiting a 1,2- or 1,3-disubstitution pattern,* are especially important as they have proven to be useful ligands in asymmetric catalysis and material science.[12, 18]

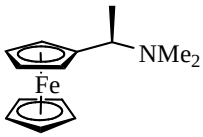
A general approach to this type of compounds involves a directed *ortho*-metalation[51] on ferrocene precursors bearing *ortho*-directing auxiliary groups with stereogenic centers (as amines **70**[52] or **71**, oxazolines **72**,[53-55] hydrazones **73**,[56] sulfoxides **74**,[57] and acetals **75**[58]) and trapping of the resulting lithium reagents with an appropriate electrophile. As a consequence, the ferrocenes resulting from the stereoselective reactions are diastereoisomers, containing elements of both planar and central chirality.

* The ferrocene molecule (**14**) is rendered chiral by the different substitution of one of the cyclopentadienyl rings. Whereas a monosubstituted ferrocene has C_s symmetry, the mirror plane is eliminated by a second, different substitutent. A ferrocene derivative with at least two different substituents at the same ring can not be superimposed with its mirror image. The two faces of the disubstituted cyclopentadienyl ring are enantiotopic and enantiomeric complexes arise from the coordination of the CpFe fragment to either one of these two faces. The term "**planar chirality**" is frequently applied to describe this stereochemical situation.

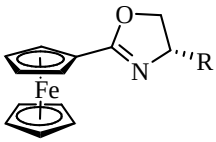
A simple rule was developed to assign chirality descriptor to homoannular, di- or polysubstituted ferrocenes: the observer regards the molecule from the side of the ring to be assigned (called the "upper" ring). The substituents are then analyzed according to the CIP rules (Cahn-Ingold-Prelog). If the shortest path from the substituents with highest priority to that following in heriarchy is clockwise the discriptor is (*R*), otherwise it is (*S*).



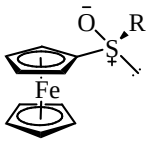
In order to show clearly that the chirality descriptors belongs to a planar element of chirality, it is often written as (*pR*) or (*pS*). When ferrocene bears both, central and planar chirality, the descriptor of the central chirality is written first.[12]



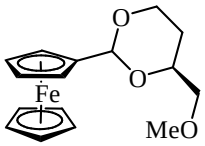
70[52]



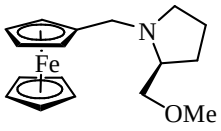
72[53 - 55]



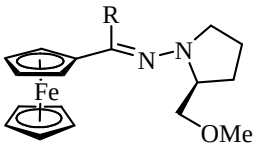
74[57]



75[58]



71



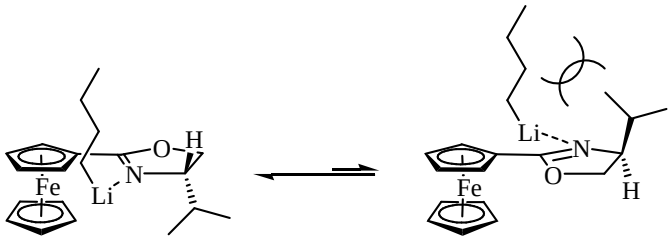
73[56]

The most common strategy to chiral 1,2-substituted ferrocenes is based on the use on Ugi´s *N*,*N*-dimethyl-1-ferrocenylethylamine (**70**), as it is readily obtained enantiomerically pure by classical resolution or asymmetric synthesis and can effectively be *ortho*-lithiated to prepare a variety of related chiral ferrocenes.[52]

In the same context, an area, which has generated a great deal of interest lately, is the synthesis of planar chiral ferrocenes taking advantage on the selective deprotonation of diastereotopic hydrogen atoms in chiral ferrocenyloxazolines, which are readily derived from commercially available optically active aminoalcohols.

Through the pioneering work of Richards,[53] Sammakia[54] and Uemura,[55] a robust and facile method for the synthesis of planar chiral 2-ferrocenyloxazolines containing secondary functional groups in both, high yield and enantiopurity, has been developed. Selective deprotonation of chiral ferrocenyloxazolines by addition of alkyllithium followed by an appropriate electrophile has been reported independently by these three groups to lead to a different ratio of diastereoisomeric products depending on the reaction conditions (solvent, temperature, base or presence of an additive).

The outcome of this reaction and the origin of the diastereoselection has been rationalized with a model in which the oxazoline substituent is oriented towards the iron atom, allowing the nitrogen-coordinated alkyl-lithium reagent to approach unconstrained from the opposite direction.



76 **77**

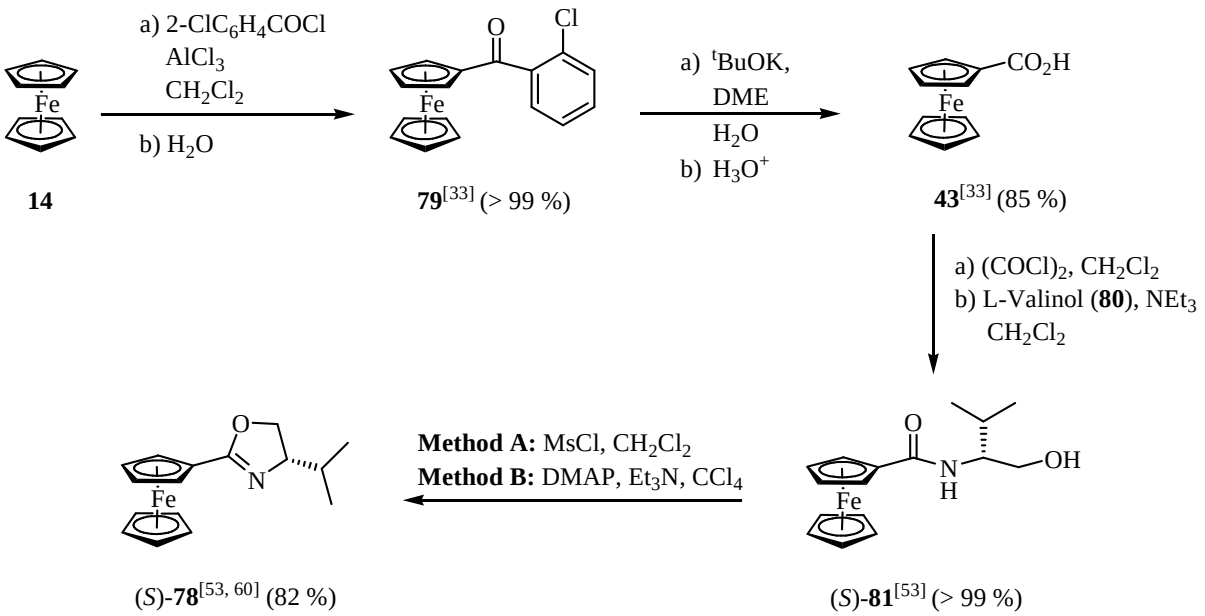
Motivated by our interest in trimetallic metallocenes we considered the applicability of one of these strategies in the asymmetric synthesis of triferrocenylmethanol derivatives bearing at one of their ferrocenyl units a 1,2-disubstituted ferrocene backbone.

3.5.1 Chiral Ferrocenyloxazolines

2-Oxazolines have been applied in numerous fields of organic chemistry.[59] This versatile heterocycle has served as protecting group, coordinating ligand, activating moiety, monomer in polymer chemistry, moderator in analytical processes, and as conformationally rigid peptide mimic in medicinal chemistry. Even natural systems have chosen to incorporate oxazolines into their chemical arsenal, as evidenced by the rapidly growing number of identified natural products and their attendant pharmacological properties.[59]

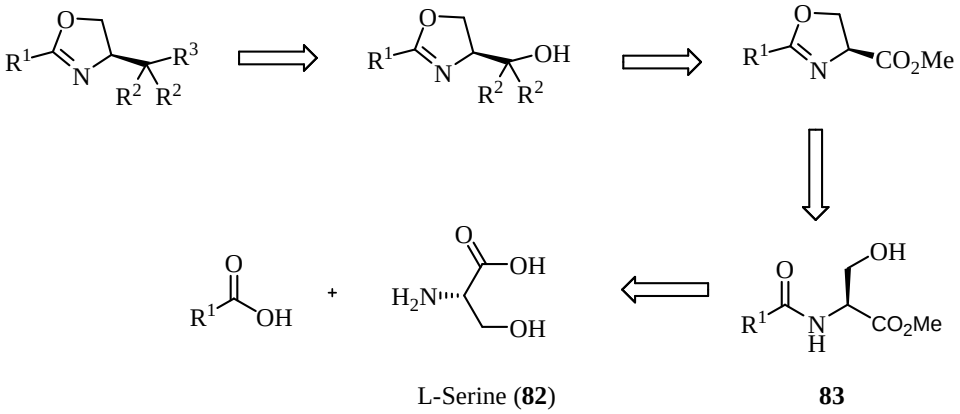
Chiral oxazolines are now firmly established as one of the most popular and successful classes of ligands for application in metal-catalyzed asymmetric transformations.[60] This is at least in part due to their ease of synthesis from readily available amino acids. L-Valine for example, has been utilised as the basis of many highly enantioselective metal-ligand systems.

(*S*)-2-Ferrocenyl-4-isopropyloxazoline (**78**) was readily prepared from ferrocenecarboxylic acid (**43**) following known literature protocols. Reaction of ferrocene (**14**) with 2-chlorobenzoyl chloride and aluminum chloride cleanly gave aryl ketone **79** which was hydrolysed to give ferrocenecarboxylic acid (**43**) in 85 %.[33] Then, ferrocenoyl chloride, generated *in situ* from ferrocenecarboxylic acid (**43**) and oxalyl chloride, was combined with L-Valinol (**80**) to yield the corresponding β-hydroxy amine **81**[53] which was subsequently cyclised and dehydrated to give (*S*)-2-ferrocenyl-4-isopropyloxazoline (**78**).[53, 60]



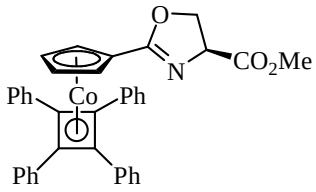
3.5.2 Chiral Ferrocenylhydroxyoxazolines

An attractive building block for the synthesis of hydroxyoxazolines is L-serine (**82**) as it potentially incorporates up to three points of diversity (R^1, R^2 and R^3). Ideally many diverse structures are obtainable from this readily available starting material allowing the synthesis of ligand libraries.

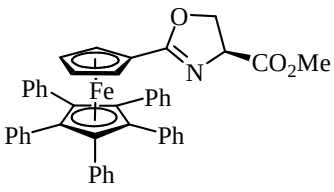


Although various methods have been reported for the dehydrative cyclisation of β-hydroxy amides **83**, many are not compatible with serine derived systems because of the competitive

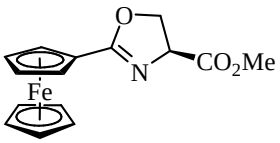
formation of dehydroamino esters.[59] A mild and effective method for the cyclisation of L-serine (**82**) derived β-hydroxy amides **83** has been reported using diethylaminosulfur trifluoride (DAST).[61] Application of this procedure to metallocene chemistry, was first developed by Richards[62] and resulted in clean transformations of the parent amides into the oxazoline esters **84** - **86** (> 95 % *ee* as determinated from the ^{1}H NMR spectra of the (*S*)- and (*R*)-Moshers esters).



(*S*)-**84**[62]

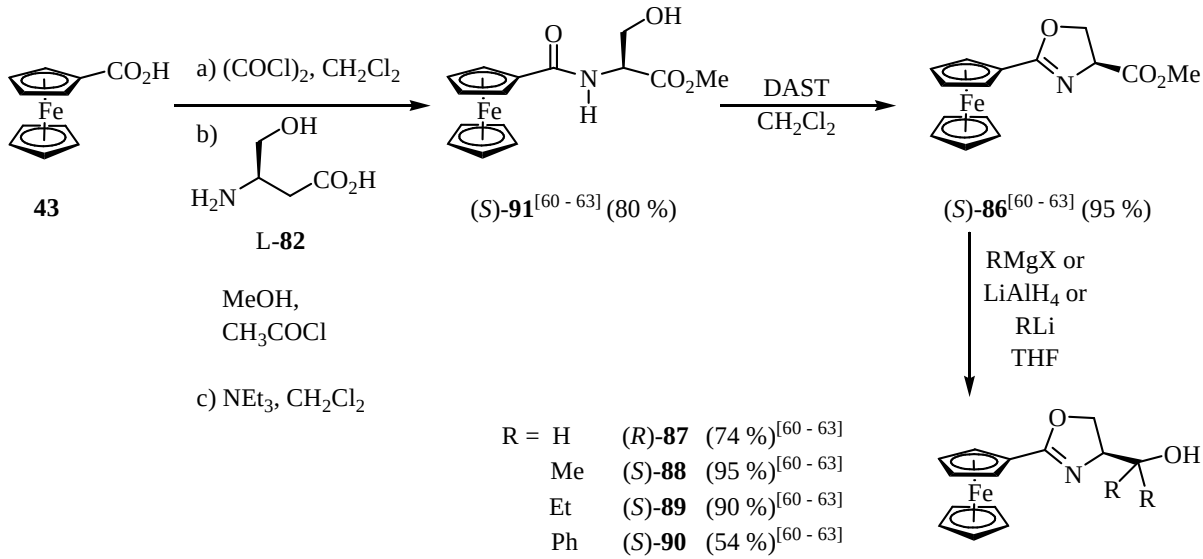


(*S*)-**85**[62]

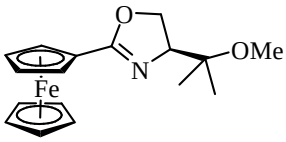


(*S*)-**86**[62]

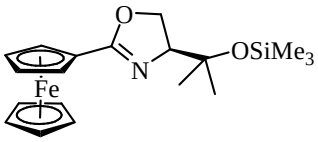
The known ferrocenylhydroxyoxazolines **87** - **90** were easily prepared in large scale following modified literature protocols:[62-65] one pot synthesis of the amide (*S*)-**91**, from L-serine (**82**) and ferrocenecarboxylic acid (**43**), followed by dehydrative cyclisation promoted by DAST and nucleophilic addition or reduction of the parent ester **86**.



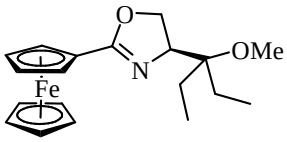
Consequently, hydroxyoxazolines **87** - **90** were transformed into the corresponding methyl ethers **92** - **95**,[65] silyl ether **96** and allyl ether **97** derivatives following modified literature protocols.[65] Interestingly, the previously unknown **96** and **97** allow the straightforward elaboration of the molecule.



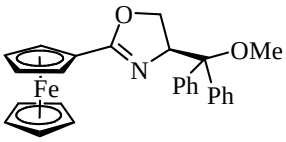
(*S*)-**92**[65] (69 %)



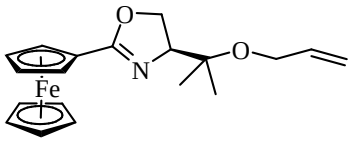
(*S*)-**96** (64 %)



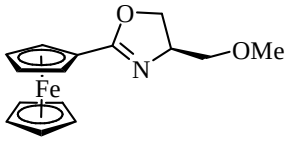
(*S*)-**93**[65] (28 %)



(*S*)-**94**[65] (66 %)



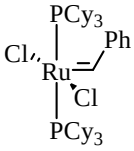
(*S*)-**97** (48 %)



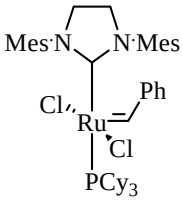
(*R*)-**95**[65] (74 %)

Moreover, through the oxazoline side chain the ferrocenyloxazoline backbone might be easily append to a resin for its use as a polymer-supported ligand.

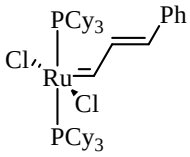
Ring opening metathesis polymerization (ROMP) has become an increasingly popular route to side-chain-functionalized polymers and copolymers. The high tolerance of ruthenium-based initiators **98** - **103**[66-68] to a variety of functional groups coupled with a high control over the polymer architectures, has moved ROMP into the forefront of polymer synthesis.



98[67]



99[68]



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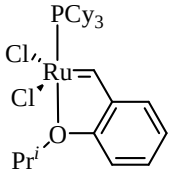

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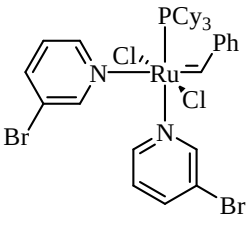

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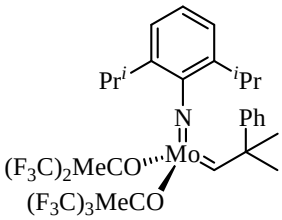
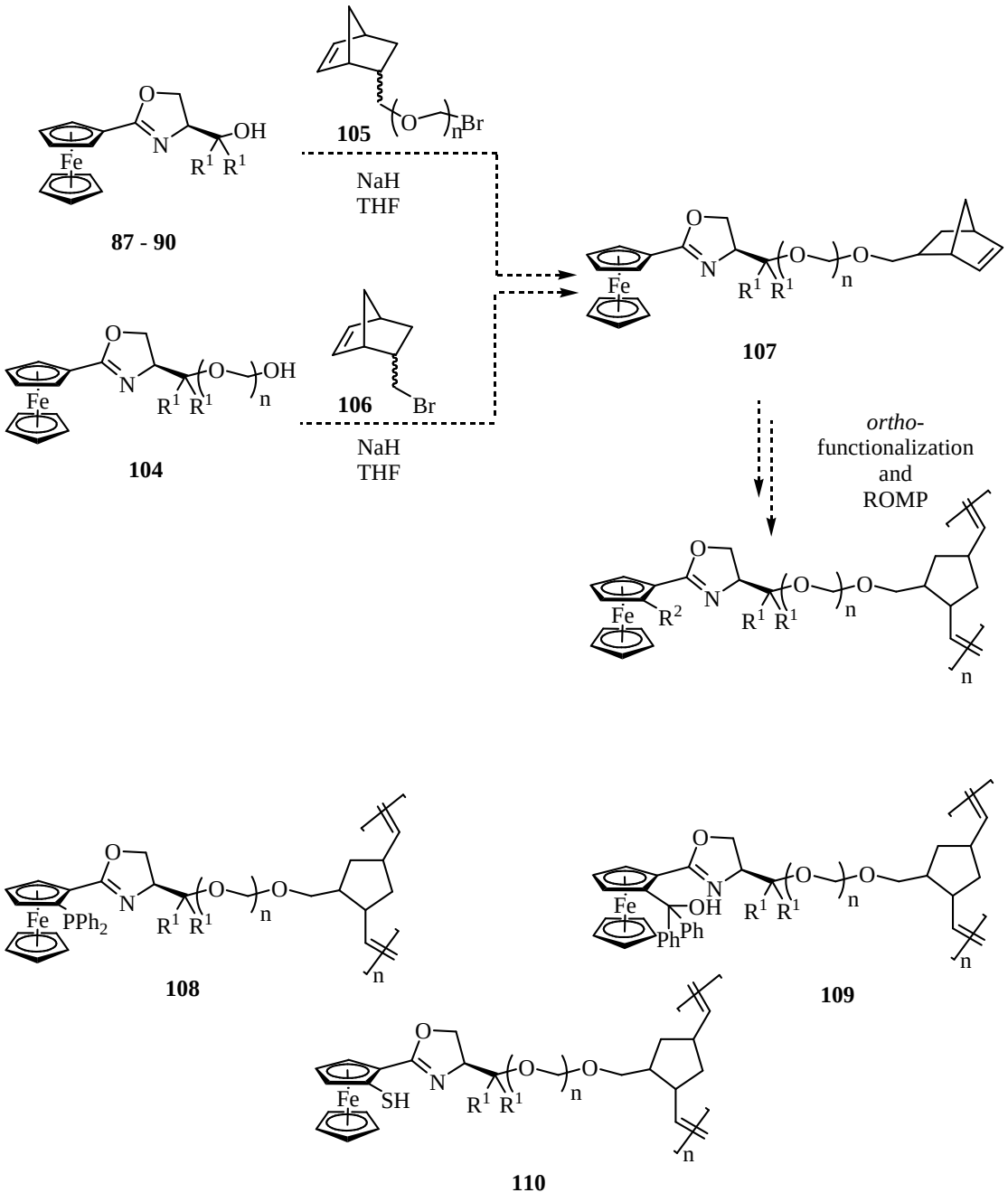


103[66]

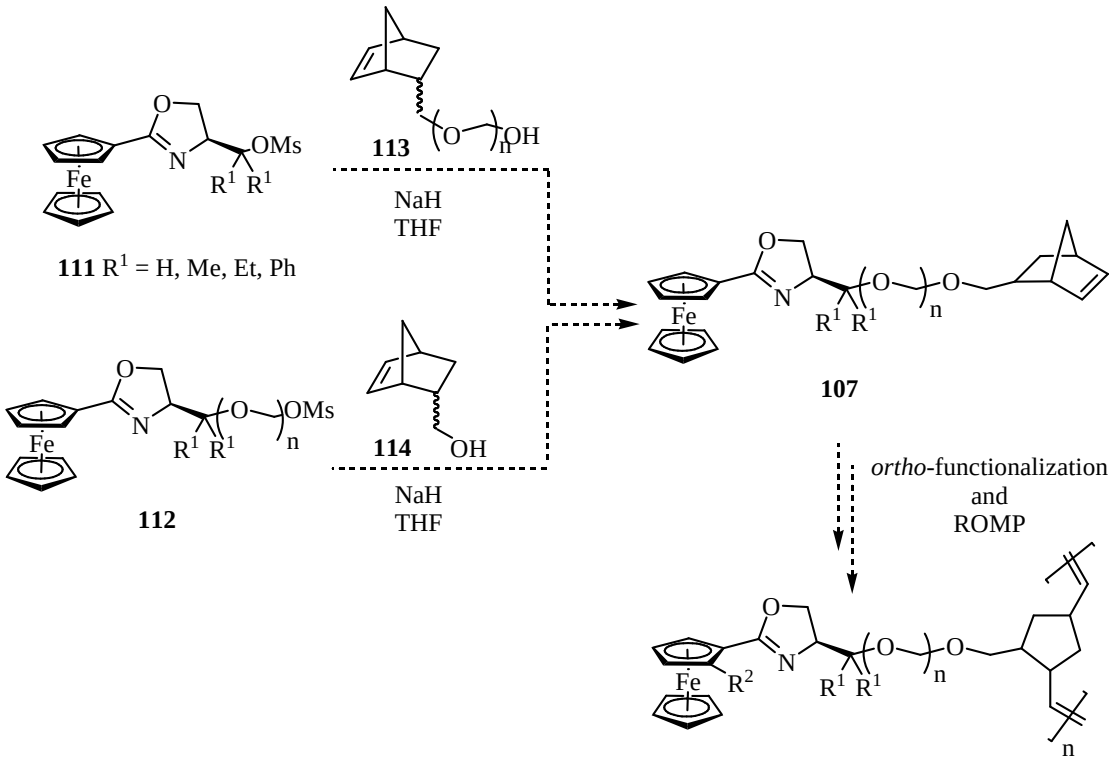
Therefore, using the already developed methodology, derivatization of the oxazoline side arm in order to append a norbornene unit, will allow the synthesis of functionalized polymers bearing a ferrocenyloxazoline backbone.

Ortho-functionalization and ring opening metathesis polymerization (ROMP) of the resulting monomer **107**, would lead to the synthesis of a functionalized polymer with an oxazoline backbone suitable for asymmetric metal catalyzed reactions.

In order to fine tune the reactivity of the polymer different spacers and *ortho*-functional groups can be easily added, just by a slight modification of the abovementioned reactions sequence (*e.g.* **108** - **110**).



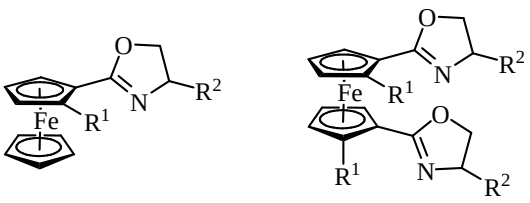
Alternatively hydroxyoxazolines **87** - **90** might be converted to intermediate mesylates **111** (R^1 = H, Me, Et, Ph) using the already developed protocol for the synthesis of **111** (R^1 = H).[62] Subsequent treatment with norbornene derivatives **113** or **114** might result in the synthesis of monomer **107**.



3.5.3 Chiral 1,2-Disubstituted Ferrocenylhydroxyoxazolines

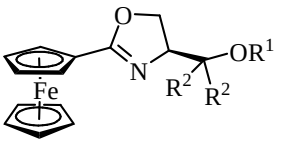
Chiral non-racemic oxazolines have found widespread application as ligands in a multitude of metal catalyzed asymmetric reactions.[27] Among these ligands the substituted ferrocenyl-oxazolines **115** or **116** constitute a special group as they posses both central and planar chirality. These oxazolines have been described independently by several groups and various types of effective planar chiral ferrocene ligands have been developed. These types of chiral ligands have been extensively and successfully applied in palladium catalyzed allylic substitutions and in asymmetric additions of Zn(II)-reagents (alkylzincs, arylzincs, alkynylzincs) to aldehydes.[60]

Nowadays, a number of groups have shown that *ortho*-lithiation of 2-ferrocenyloxazolines and *in situ* quenching with various electrophiles provides a highly selective method for the synthesis of enantiopure *ortho*-substituted 2-ferrocenyloxazoline derivatives. In this way, a wide range of mono- and dioxazolineferrocenes **115** and **116** have been prepared, mostly variations of the oxazoline side arm (R^2) or the nature of the secondary functional group (R^1).[60]



115 **116**

An important advance in the design of ferrocenyloxazolines, should be the synthesis of specifically functionalized derivatives possessing a tertiary chelating group. In this respect, the previously reported hydroxyoxazolines **96 - 97** can be regarded as precursors of 1,2-disubstituted derivatives incorporating a masked functionality at the oxazoline side arm.



(*S*)-**96** R^1 = Me R^2 = $SiMe_3$
(*S*)-**97** R^1 = Me R^2 = Allyl

The modular synthetic approach to this kind of ligands represents one of their most important features. Indeed, it should be possible to vary the nature of the fragments attached to the ferrocenyloxazoline backbone in a few steps to expeditiously fine tune both the steric and the electronic properties of the ligands, according to the needs of a particular reaction.

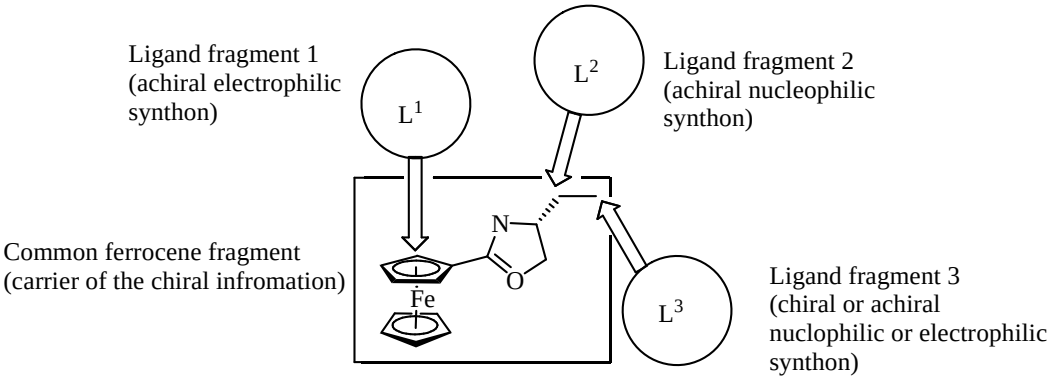


Figure 3. Common ferrocene fragment (carrier of the chiral information).

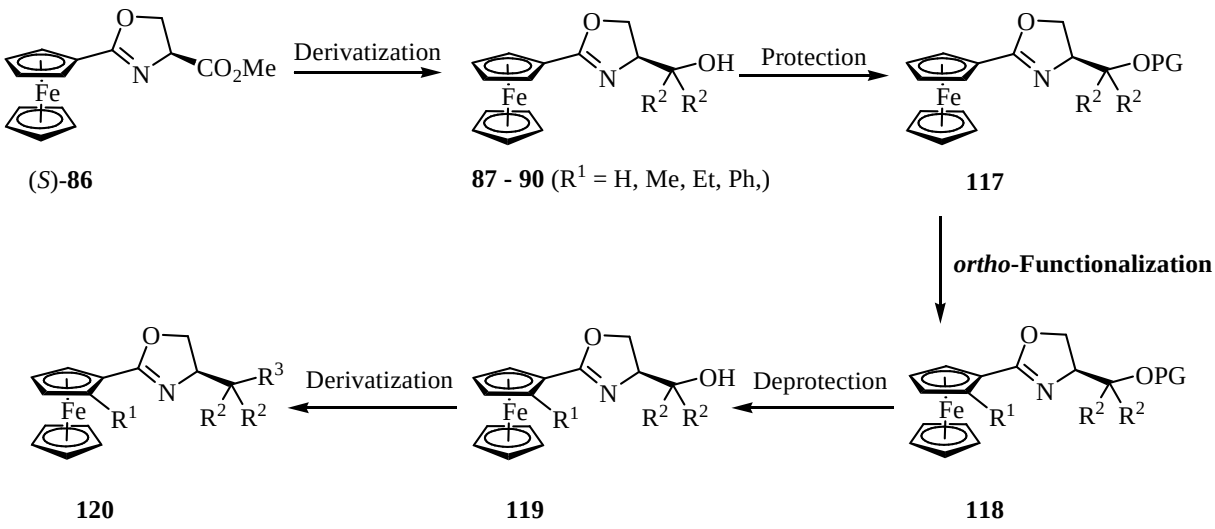


Figure 4. Proposed synthetic sequence for the synthesis of trisubstituted ferrocenyloxazolines **120**.

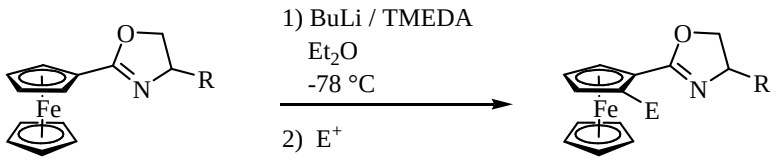
It is noteworthy that the bottleneck in this synthetic sequence (**Figure 4**) is expected to be the *ortho*-functionalization of the protected ferrocenylhydroxyoxazolines **117**.

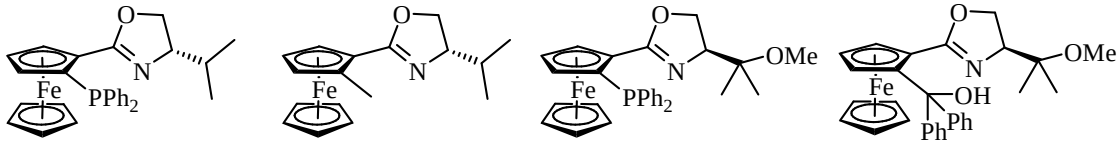
After a brief survey of the literature, it was found that 1,2-substituted protected ferrocenylhydroxyoxazolines **118** have been prepared by diastereoselective deprotonation of the parent oxazolines albeit with low selectivity.[65]

In 1995, Sammakia developed what is now regarded as the method of choice for the *ortho*-lithiation of 2-ferrocenyl-4-alkyloxazolines.[54] It was shown that the combination of an additional chelating ligand, such as tetramethylethylenediamine (TMEDA) and the correct selection of solvent could vary the selectivity of the reaction dramatically.

Despite the fruitful use of this methodology in the synthesis of substituted ferrocenyloxazoline ligands, to the best of our knowledge, its application to the selective deprotonation of ferrocenylhydroxyoxazolines **117** has not been reported until now.

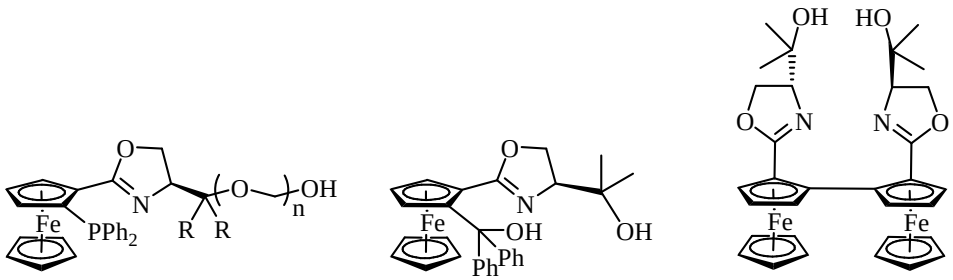
Thus, diastereoselective *ortho*-lithiations of oxazolines (*S*)-**78** or (*S*)-**92**, with BuLi in Et_2O and in the presence of TMEDA, followed by addition of an electrophile under slightly modified Sammakia reaction conditions, lead to the diastereomerically enriched 1,2-disubstituted ferrocenes **121 - 124** (> 95 % *dr*, only one diastereoisomer was detected by ^{1}H NMR or ^{13}C NMR after column chromatography).



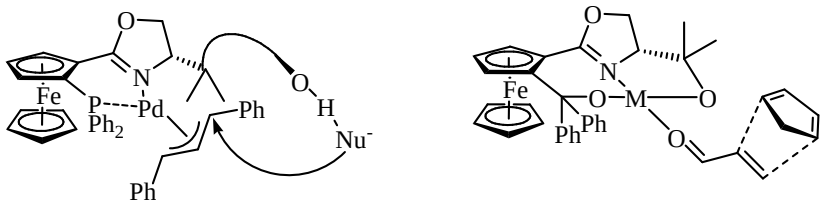


(*S*,*S*p)-**121**[53- 55] (72 %) (*S*,*R*p)-**122**[53- 55] (88 %) (*S*,*S*p)-**123** (31 %) (*S*,*R*p)-**124** (63 %)

The extension of these ligands to entirely new asymmetric catalytic processes can be anticipated (*e.g.* as new three- or tetra-dentate ligands or as new chiral oxazoline ligands with secondary binding sites to enhance the selectivity of the catalytic reaction).



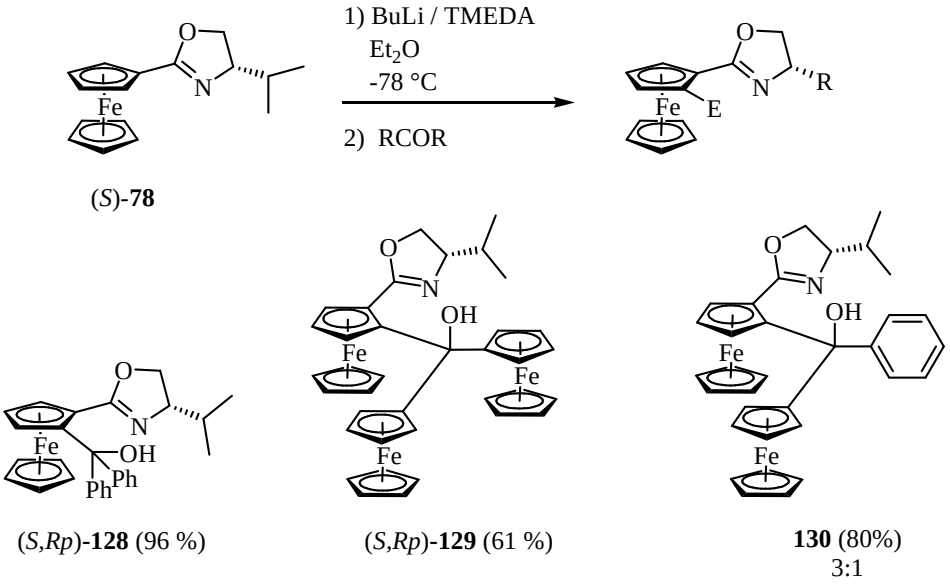
125 (*S*,*Rp*)-**126** **127**



M = Zn, Cu, Ti, *etc*.

3.5.4 Chiral 1,2-Disubstituted Ferrocenyloxazolines

In connection with our interest concerning the synthesis of new of triferrocenylmethanol derivatives bearing a 1,2-disubstituted ferrocene backbone, diastereoselective *ortho*-lithiation of (*S*)-2-ferrocenyl-4-isopropyloxazoline (**78**), followed by addition of a carbonyl substrate [benzophenone, ferrocenylphenylketone and diferrocenylketone (**40**)] under modified Sammakia reaction conditions, gave the diastereomerically enriched (> 95 % *dr*, only one diastereoisomer was detected by ^{1}H NMR after column chromatography) 1,2-disubstituted ferrocenes **128** - **130**.



To the best of our knowledge, this is the first asymmetric synthesis of a chiral triferrocenylmethane derivative as (*S,Rp*)-**129**. This methodology however, has a clear disadvantage in that it is only suitable for the synthesis of the oxazoline derivatives

All new ferrocenes are air-stable solids that give the expected analytical and spectroscopic data. Interestingly, for all of the compounds, the hydroxyl proton is strongly coordinated to the nitrogen atom of the oxazoline moiety, resulting in a stable seven-membered chelate ring. As a consequence in the ^{1}H NMR spectra these protons show significant downfield to values around δ = 9.0 and 9.6 ppm.

It was possible to crystallize diphenylhydroxymethylferronyloxazoline (*S,Rp*)-**128**. Its solid-state structure shows one equatorial phenyl group while the other phenyl substituent occupies

an axial position with regard to the cyclopentadienyl backbone. Such conformation is common for those ferrocene derivatives which bear two bulky groups in the α-position. Because the hydroxy proton is chelated within a seven membered ring, the relative position of the isopropyl group towards the axial phenyl substituent is firmly attached, resulting in an overall fixed conformation.

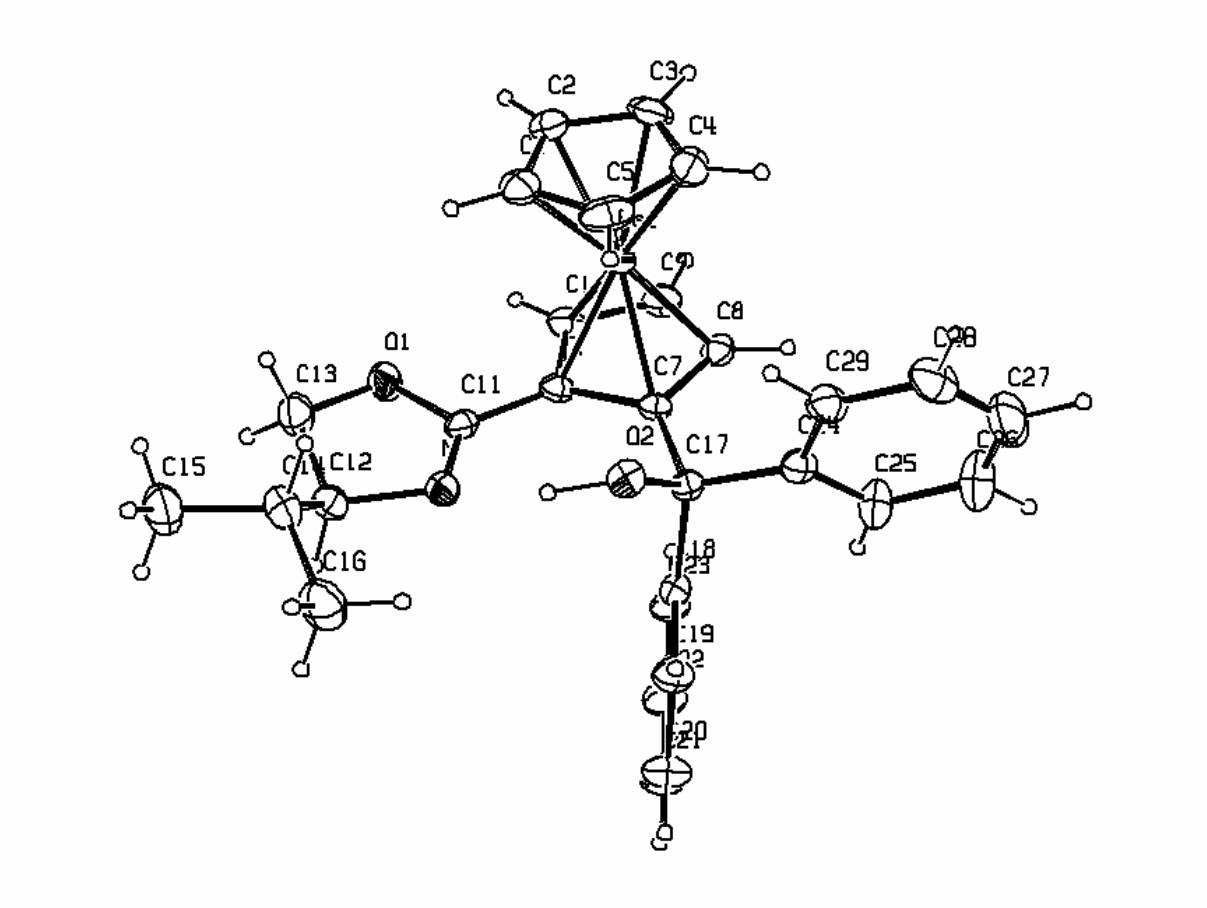


Fig. 5: ORTEP drawing of the structure of (*S*,*Rp*)-**128** in the crystal. Selected bond lengths [Å], angles [°] and dihedral angles [°]: O2-C17-C7 111.0(3), N-C11-C6 128.8(3), N-C12-C14 112.4(3), C7-C6-C11 128.8(3), N-C11-C6-C7 –7.0, N-C11-C6-C10 176.7, O1-C11-C6-C10 –4.8, O1-C11-C6-C7 171.5, O2-C17-C7-C6 –50.9, O2-C17-C7-C8 137.6, C26-C24-C17-C7 92.0, C25-C24-C17-C7 –84.8, C23-C18-C17-C7 20.4, C19-C18-C17-C7 –161.9, C19-C18-C17-C24 78.0, C23-C18-C17-C24 –99.6, C25-C24-C17-C18 35.7, C29-C24-C17-C18 –46.9, C29-C24-C17-C7 92.6, C25-C24-C17-C18 –84.8.

Crystallization of (*S*,*Rp*)-2-(2-diferrocenylhydroxymethylferrocenyl)-4-isopropyloxazoline (**129**) from TBME gave traces of a material suitable for X-ray crystal structure analysis. Discouragingly, the spectra corresponded to 1,1-di(ferrocenyl)pentanol (**131**) which might

have arisen from the addition of an excess of BuLi to diferrocenylketone (**40**) in the course of the reaction.

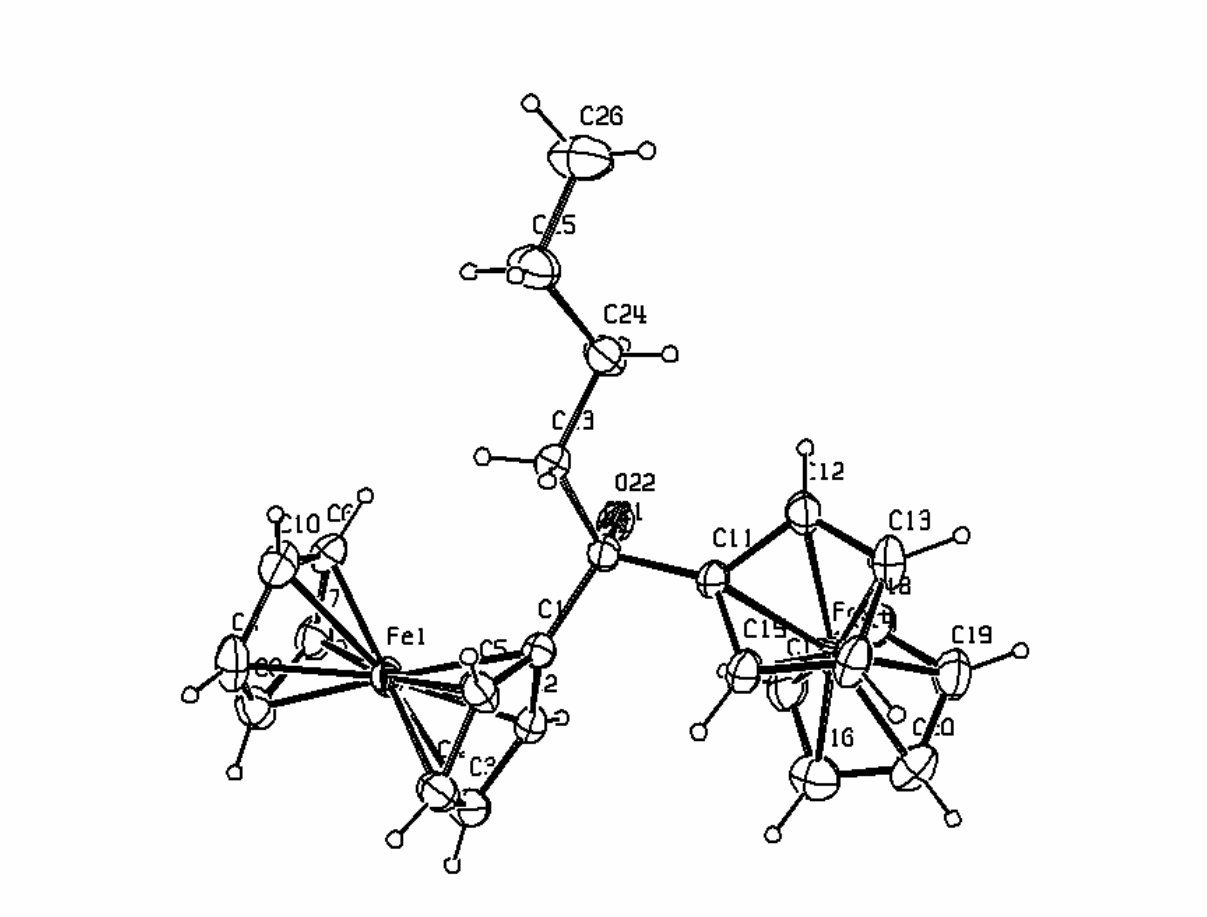


Fig. 6: ORTEP drawing of the structure of **131** in the crystal. Selected bond lengths [Å], angles [°] and dihedral angles [°]: C1-C21 1.514(11), C11-C21 1.523(10), C21-O22 1.458(9), C21-C23 1.511(12), C23-C24 1.513(12), C24-C25 1.489(15), C25-C26 1.496(15), C5-C1-C21 126.3(8), C2-C1-C21 127.5(8), O22-C21-C23 108.3(7), O22-C21-C1 108.8(6), C23-C21-C1 111.7(7), O22-C21-C11 107.4(6), C23-C21-C11 112.7(7), C1-C21-C11 107.8(7), C21-C23-C24 117.5(8), C25-C24-C23 111.6(8), C24-C25-C26 113.6(11), C12-C11-C21-O22 53.0, C2-C1-C21-O22 27.7, C15-C11-C21-C23 107.0, C5-C1-C21-C23 –39.8, C14-C15-C11-C12 0.5, C2-C1-C5-C4 0.7, C11-C21-C23-C24 64.3, C21-C23-C24-C25 167.2, C23-C24-C25-C26 –178.1.

3.6 Application of Ferrocenyloxazolines (*S,Rp*)-128 and (*S,Rp*)-129 in Asymmetric Synthesis

3.6.1 Asymmetric Addition to Aldehydes

Carbon-carbon bond forming reactions are at the heart of organic synthesis. Many methods have been developed to accomplish this key construction. One of the most common approaches to an extension of the carbon framework involves addition reactions, usually accomplished with Grignard and organolithium reagents.

Demands for increased functional group tolerance and enantioselective variants, however, have reduced the attractiveness of such strongly basic and reactive reagents. The search for milder organometallic reagents capable of addition to aldehydes and ketones was, therefore, reinitiated. Among the possible organometallic reagents (allylstannanes, -silanes, or -boranes, *etc*.) available for the asymmetric catalytic version of this reaction, zinc(II) reagents have received special attention due to the development of chiral catalysts that enable improvement of the activity, the chemoselectivity and the enantioselectivity of the addition.[69-75]

The addition of nucleophiles to prochiral carbonyl substrates or imines is an important and well established process in organic synthesis. New stereogenic centers and carbon-carbon bonds are formed in a single step allowing the preparation of useful intermediates in the synthesis of complex natural compounds. Starting from the seminal contributions of Noyori,[69] hundreds of chiral catalyst systems have been synthesised and tested in one privileged reaction: the addition of Et_2Zn to aldehydes. Although the products of this type of reaction are of little practical interest, this well documented reaction has become a standard test reaction to study the catalytic properties of newly prepared ligands.

The reaction is easy to perform, reproducible and in absence of the catalyst the reaction proceeds sluggishly, and often reduction of the aldehyde to the alcohol is observed. It is now well established that the asymmetric alkylation of aldehydes by means of diorganozinc reagents is effectively catalyzed by various bidentate ligands such as diamines,[71] cichona alkaloids,[73] proline,[70] TADDOLs,[74] ephedrine[72] and ß-amino alcohols derivatives.[69, 75]

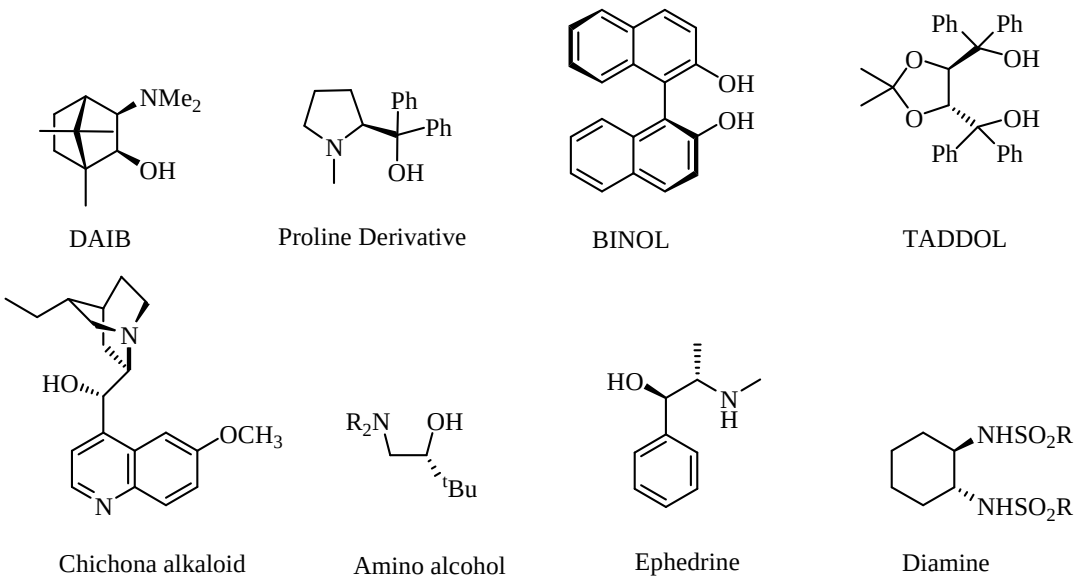


Figure 7. Common bidentate ligands for the asymmetric alkylation of aldehydes by means of diorganozinc reagents.

The mechanism of the asymmetric addition of dialkylzinc to aldehydes has been subject of intense research. A convincing mechanism based on experimental and theoretical investigations was proposed by Noyori.[76, 77] The true asymmetric catalyst is believed to be a zinc alkoxide **132** where the nitrogen atom of the amino alcohol ligand coordinates to zinc. This alkoxide **132** acts as a bifunctional catalyst, at which an aldehyde substrate can coordinate to the Lewis acidic zinc atom, and the Lewis basic oxygen can coordinate to a dialkylzinc molecule. Attack of the diethylzinc at the carbonyl carbon atom in intermediate **134** yields the alkoxide **136**, which is converted back to the complex **135** or **133** upon addition of diethylzinc or aldehyde, respectively. The zinc alkoxide **137** is split off during this conversion. Workup of this alkoxide **137** affords the alcohol.[77, 78]

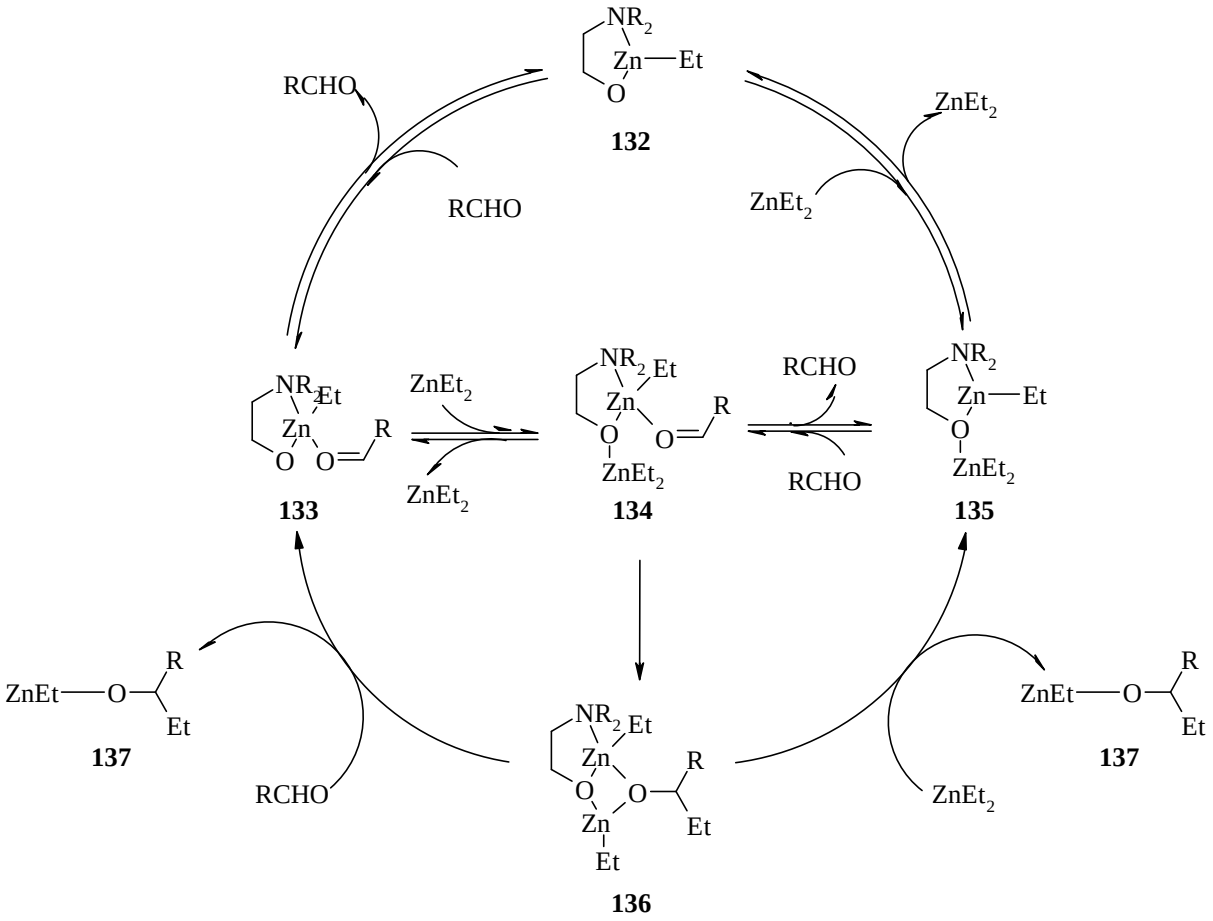
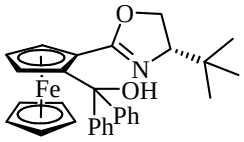


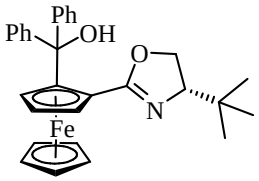
Figure 8. Proposed mechanism for the asymmetric alkylation of aldehydes by means of diorganozinc reagents.[76-78]

3.6.2 Enantioselective Addition of Diethylzinc to Aldehydes

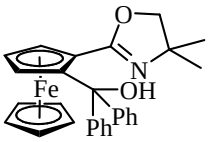
The report by Bolm on the asymmetric addition of diethylzinc to aldehydes catalzed by hydroxymethylferrocenyloxazolines **138 - 140**[79] initiated an intense research in this area and shortly thereafter structurally related ligands were described (*e.g.* **141** or **142**).[80-82]



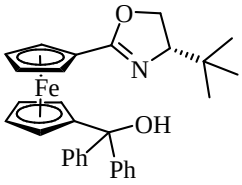
(*S*,*Rp*)-**138**[79]



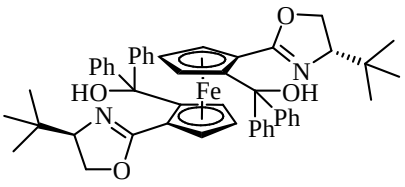
(*S*,*Sp*)-**139**[79]



(*Rp*)-**140**[79]



(*S*)-**141**[81]



142[80, 82]

In this first communication, Bolm pointed out the cooperative synergic action between central and axial chirality by comparing the performance of hydroxymethylferrocenyl-oxazolines **138 - 140** in the catalytic addition of Et_2Zn to aldehydes.*

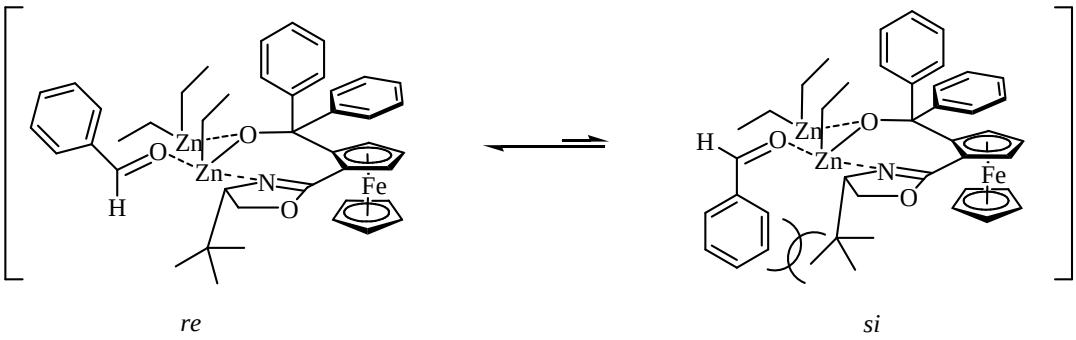
The hydroxymethylferrocenyloxazoline scaffold holds substituents in a well defined spatial proximity suitable for metal coordination. The hydroxy proton is chelated within a seven membered ring fixing the arrangement of the whole molecule. Upon complexation with zinc, a rigid conformation was assumed with one phenyl group located in equatorial position and the other one in an axial position (as it was reasoned that the replacement of the chelated proton by an ethylzinc moiety should not lead to any significant structural distortion). Such

* For most catalytic systems involving chiral ferrocene derivatives with both central and planar chirality, the effects of the chirality elements on the enantioselectivity in the catalyzed reaction have been studied. It is widely accepted that the element of planar chirality in most systems is decisive for exerting control over both absolute configuration and enantiomeric excess. However, Bolm successfully demonstrated that in the Et_2Zn asymmetric alkylations of aldehydes with ferrocene-oxazolines based catalysts (**138 - 140**) the planar chirality alone is not sufficient for high enantioselectivity.

By comparing the impact of the elements of planar or central chirality on the stereochemical outcome of the reaction, Bolm claimed, that the right combination of the stereoelements and their mutual interactions were of major importance for achieving high enantioselectivities. These results were in concordance with the so-called principle of chiral cooperativity representing Masamunes matched / mismatched cases for internal stereoelements introduced by Togni for the gold asymmetric aldol reaction.[79]

conformation is common for these ferrocenes derivatives which bear two bulky groups in the α-position.

The stereochemical outcome was explained by considering a chairlike transition state, in concordance with Noyori´s models, where the substrate was coordinated in such an orientation that its large phenyl group was opposite to the oxazoline *tert*-butyl group. The transfer will then occur from the *re* side of the aldehyde giving a *R*-configurated alcohol.

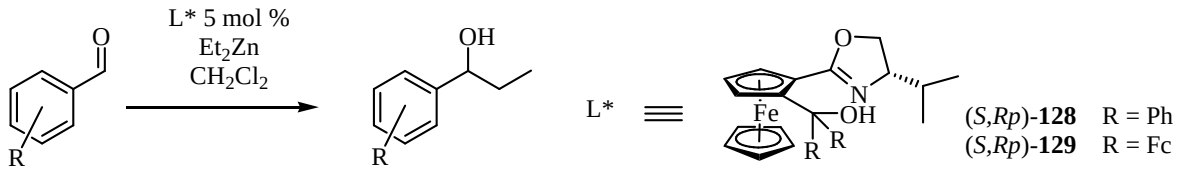


re *si*

Figure 9. Proposed transition state for the asymmetric alkylation of aldehydes by means of diorganozinc reagents catalyzed by diphenylhydroxymethylferrocenyloxazolines.[79]

The catalytic properties of the new hydroxymethylferrocenyloxazolines (*S,Rp*)-**128** and (*S,Rp*)-**129**, were explored in the asymmetric addition of diethylzinc to aryl aldehydes. These compounds have the same oxazolinyl-substituted ferrocene backbone but differ in the hydroxyl-bearing side chain. The resulting steric and electronic modifications are expected to have a remarkable impact on the examined catalyst system and alter its activity and selectivity.

The results of these studies are summarized in **Table 2**. For comparison, literature data (yield and enantiomeric excess) obtained with Bolm´s catalyst (*S,Rp*)-**138** in the catalytic addition of diethylzinc to aldehydes is listed as well.



Entry	Aldehyde	Cat.	Reaction Time [h]	Yield[a] [%]	*ee* [%]	Conf.[d]
1	C_6H_5CHO	(*S,Rp*)-**128**	24	97	83[b]	R
2[e]	C_6H_5CHO	(*S,Rp*)-**138**	6	83	93	R
3	C_6H_5CHO	(*S,Rp*)-**129**	24	95	97[b]	R
4	p-ClC_6H_4CHO	(*S,Rp*)-**128**	24	80	85[b]	R
5[e]	p-ClC_6H_4CHO	(*S,Rp*)-**138**	6	94	86	R
6	p-ClC_6H_4CHO	(*S,Rp*)-**129**	24	80	97[b]	R
7	PhCH=CHCHO	(*S,Rp*)-**128**	24	87	70[b]	R
8[e]	PhCH=CHCHO	(*S,Rp*)-**138**	6	89	78	R
9	PhCH=CHCHO	(*S,Rp*)-**129**	24	99	80[b]	R
10	p-$MeOC_6H_4CHO$	(*S,Rp*)-**128**	24	98	84[b]	R
11[e]	p-$MeOC_6H_4CHO$	(*S,Rp*)-**138**	9	93	91	R
12	p-$MeOC_6H_4CHO$	(*S,Rp*)-**129**	24	95	90[b]	R
13	1-Naphtaldehyde	(*S,Rp*)-**128**	24	94	90[c]	R
14[e]	1-Naphtaldehyde	(*S,Rp*)-**138**	-	-	-	-
15	1-Naphtaldehyde	(*S,Rp*)-**129**	24	98	97[c]	R

a) Isolated yield in % based on aldehyde. b) Determined by GC. c) Determined by ^1H NMR. d) Configurations were assigned by comparison with the sign of the specific rotation of known compounds. e) literature data.[79]

Table 2. Catalyzed asymmetric ethyl transfer to various aldehydes.

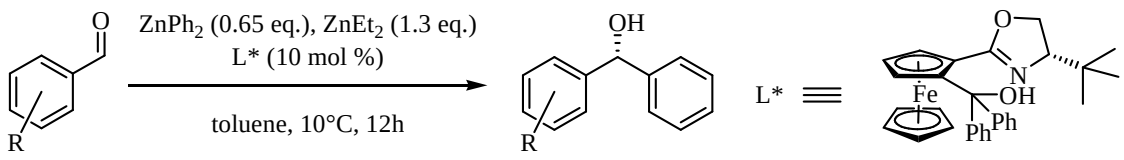
Both hydroxymethylferrocenyloxazolines (*S,Rp*)-**128** and (*S,Rp*)-**129** showed good enantioselectivities (up to 98 % *ee*) and afforded alcohols in high yields. The best results were obtained with triferrocenylmethane based oxazoline (*S,Rp*)-**129**, achieving in nearly all cases an improvement of yield or enantioselectivity compared to (*S,Rp*)-**128** or to Bolm´s (*S,Rp*)-**138**.

3.6.3 Enantioselective Arylation of Aryl Aldehydes

Chiral diaryl methanols are important intermediates for the synthesis of biologically active compounds. Two general approaches exist for their catalytic enantioselective synthesis: the enantioselective reduction of the corresponding unsymmetrical diaryl ketones,[83] or the enantioselective phenyl transfer onto aromatic aldehydes.[84] However, both methods have severe limitations and work only for a limitated range of substrates. The reduction methodology requires an *ortho* substituent or electronically very different aryl groups, and in the addition to aldehydes only phenyl transfer reactions have been developed to yield arylphenylmethanols.

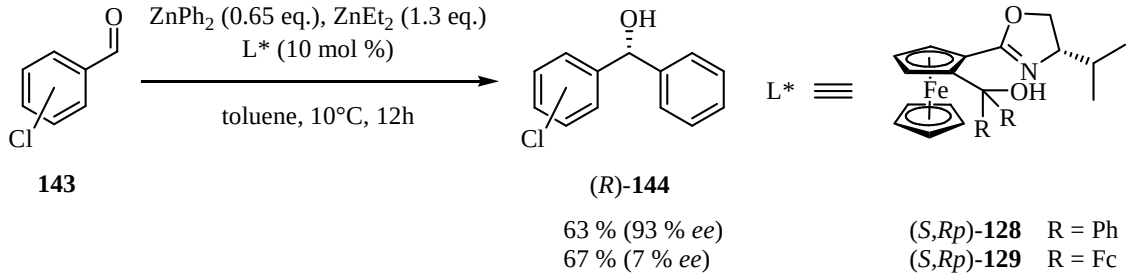
Despite, significant progress with respect to selectivity and substrate scope achieved for the asymmetric catalytic addition to aldehydes, in most of the processes the prescribed starting nucleophiles are not commercially available, are either pyrophoric or have adverse effect on the environment, and are often not amenable to prolonged storage and must therefore be utilised shortly after preparation.

Bolm developed a protocol which utilised ferrocene-based catalyst (*S,Rp*)-**138** and boron reagents (aryl boronic ester, aryl boronic acid and triphenylboran) in combination with diethylzinc as the aryl source. Enantiomerically enriched diarylmethanols with excellent enantiomeric excesses (up to 98% *ee*) were thus obtained in a straightforward manner.[85]



64 - 99 % (91 -98 % *ee*) (*S,Rp*)-**138**

In collaboration with the Bolm group, the catalytic properties of hydroxymethylferrocenyl-oxazolines (*S,Rp*)-**128** and (*S,Rp*)-**129** were tested in the asymmetric phenyl-transfer from organozinc reagents to chlorobenzaldehyde **143** giving diarylmethanol (*R*)-**144**.



143 (*R*)-**144**

63 % (93 % *ee*)
67 % (7 % *ee*)

(*S,Rp*)-**128** R = Ph
(*S,Rp*)-**129** R = Fc

Disappointingly the performance of the triferrocenylmethyl derivative (*S,Rp*)-**129**, did not fulfil our expectations. Although isopropyloxazoline (*S,Rp*)-**128** gave similar results to Bolm´s system (*S,Rp*)-**138**, the steric demanding (*S,Rp*)-**129**, gave nearly no stereoselection in spite of a respectable yield.

Assuming a similar mechanism as the one proposed for the diethylzinc addition to aldehydes, as well as a similar chair-like transition state, it is possible that in the arylation reaction the large ferrocenyl units of (*S,Rp*)-**129** hamper somehow the normal approach of the substrate (or at least alter it), thereby leading to a different set of transition states (with respect to the diethylzinc case) where no good stereodifferentiation is possible.

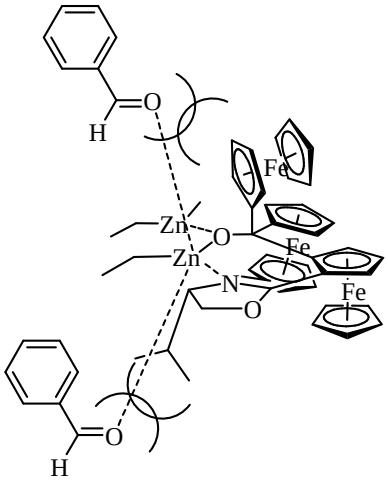


Fig 10. Proposed approach of the aldehyde.

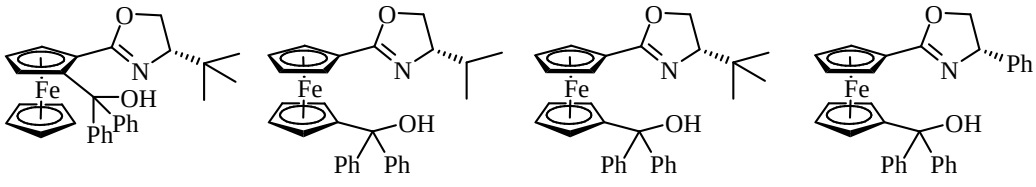
Oxazolines are among the most universally useful ligands; nonetheless, optimal ligand structures vary from one substrate to another, even within a single reaction type. These results point out that for achieving high enantioselectivities, the right combination of stereoelements is necessary as well as the right cooperative interactions between the system substrate-reagent-catalyst.

3.6.4 Enantioselective Phenylacetylene Addition to Aldehydes

Chiral propargylic alcohols are useful building blocks for the enantioselective synthesis of complex molecules. Their utility is amply demonstrated in numerous elegant syntheses that have employed such carbinols as key starting materials.[86, 87] The methods which have been devised for the asymmetric synthesis of optically active propargylic alcohols involve either nucleophilic addition of metalated acetylenes (stannyl, boryl or zinc) to aldehydes or ynone reduction.

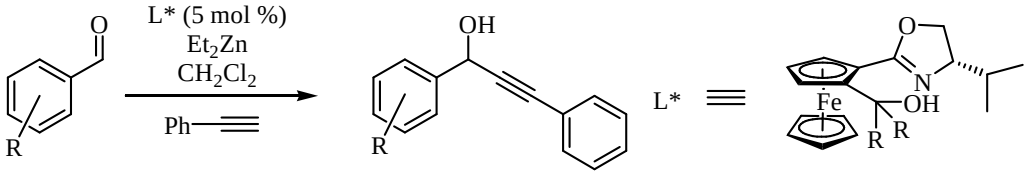
In recent years, significant progress has been made in the catalytic enantioselective addition reactions of acetylenes to aldehydes[88, 89] and many chiral ligands, such as *N*-methyl-ephedrine, BINOL and its derivatives and other aminoalcohol derivatives, have successfully been used in this reaction. Among the asymmetric alkyne additions to aldehydes the use of alkynylzinc reagents is the most widely studied. Alkynylzinc can be directly prepared *in situ* from the reaction of terminal alkynes with commercially available alkylzinc reagents. In addition, alkynylzinc reagents also tolerate compounds with many functional groups such as ketones, esters, amides, nitro groups, and nitriles.

Most recently, the use of chiral ferrocenyloxazoline ligands could be extended to the asymmetric addition of phenylacetylene to aldehydes in the absence of other metal reagents except diethylzinc. Ligands (*S,Rp*)-**138**, (*S*)-**141**, (*S*)-**145** and (*S*)-**146** afforded moderated to good enantiomeric excesses with a variety of different aldehydes.[90]



(*S,Rp*)-**138**[90] (*S*)-**145**[90] (*S*)-**141**[90] (*S*)-**146**[90]

Therefore ligands (*S,Rp*)-**128** and (*S,Rp*)-**129** were tested in the asymmetric addition of phenylacetylene to aldehydes for the synthesis of propargylic alcohols under the reported optimized reaction conditions.[90]



(*S,Rp*)-**128** R = Ph
(*S,Rp*)-**129** R = Fc

Entry	Aldehyde	Cat.	Yield[a] [%]	*ee*[b] [%]	Conf.[c]
1	C_6H_5CHO	(*S,Rp*)-**128**	75	5.4	*R*
2	C_6H_5CHO	(*S,Rp*)-**128**	42	1.3	*R*
3	C_6H_5CHO	(*S,Rp*)-**129**	58	1.22	*S*
4	p-ClC_6H_4CHO	(*S,Rp*)-**128**	40	18.7	-[d]
5	PhCH=CHCHO	(*S,Rp*)-**128**	33	6.4	-[d]
6	PhCH=CHCHO	(*S,Rp*)-**129**	65	14.6	-[d]
7	p-$MeOC_6H_4CHO$	(*S,Rp*)-**128**	76	16.5	-[d]
8	p-$MeOC_6H_4CHO$	(*S,Rp*)-**129**	55	18.6	-[d]
9	1-Naphtaldehyde	(*S,Rp*)-**128**	92	-[d]	-[d]
10	1-Naphtaldehyde	(*S,Rp*)-**129**	70	-[d]	-[d]

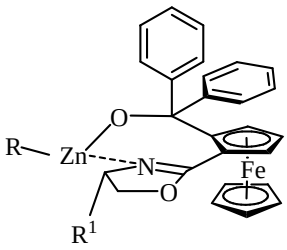
a) Isolated yield in % based on aldehyde. b) Determined by HPLC. c) Configurations were assigned by comparison with the sign of the specific rotation of known compounds. d) Not determinated.

Table 3. Catalyzed asymmetric alkynyl transfer to various aldehydes.

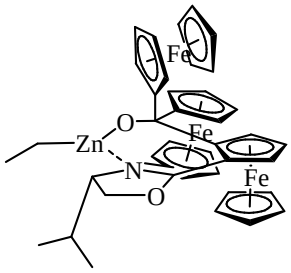
In this preliminary study terminal phenylacetylenes underwent addition to aryl aldehydes in respectable yields, but with low stereoselectivity (1 - 18 % *ee*). In nearly all cases the

presence of the ethyl addition product could be detected (possibly due to the competitive addition of the ethyl substituent at the zinc reagent).

It is commonly accepted that in order to get fairly high selectivities in this type of reaction it is sufficient to have a ligand, which blocks one face of the catalyst reasonably well.[78] In the hydroxymethylferrocenyloxazoline systems, one can assume that the substrate will approach the metal atom from the side opposite to the large substituent at the oxazoline ring [this substituent blocks one side of the molecule as shown by the calculated structure of the proposed active catalyst **147** (R = Me, R^1 = *tert*-butyl) for the asymmetric alkylation of aldehydes by means of diorganozinc reagents catalyzed by hydroxymethylferrocenyl-oxazoline (*S*,*Rp*)-**138**].[91]



147



148

Figure 11. Proposed active catalysts for the asymmetric alkylation of aldehydes by means of diorganozinc reagents catalyzed by hydroxymethylferrocenyloxazolines (*S*,*Rp*)-**128**, (*S*,*Rp*)-**138** or (*S*,*Rp*)-**129**.

The approach of the aldehyde may lead then to intermediates **150** or **151.** Comparison of these two structures shows that steric interactions will find higher expression in **151**, and therefore, intermediate **150** should be favored.* The transfer will then occur from the *re* side of the aldehyde giving a *R*-configurated alcohol.

The foreseen reaction pathway seems appropriate to explain our results. It is immediately obvious that the proposed active catalysts **147** and **148** are very crowded, in particular around

* in contrast to the intermediate proposed by Bolm,[79] where the substituent at the metal atom and the aryl group of the aldehyde are at the same side, in intermediate **150** the phenyl group at the aldehyde coordinates opposite to the group at the oxazoline and opposite to the substituent at the zinc atom.

the alkoxy oxygen, which will coordinate the stoichiometric zinc reagent in the transition state. It is then reasonable to assume that the stereochemical outcome of the reaction might depend on the right combination of bulk in the ligand and in the zinc reagent.

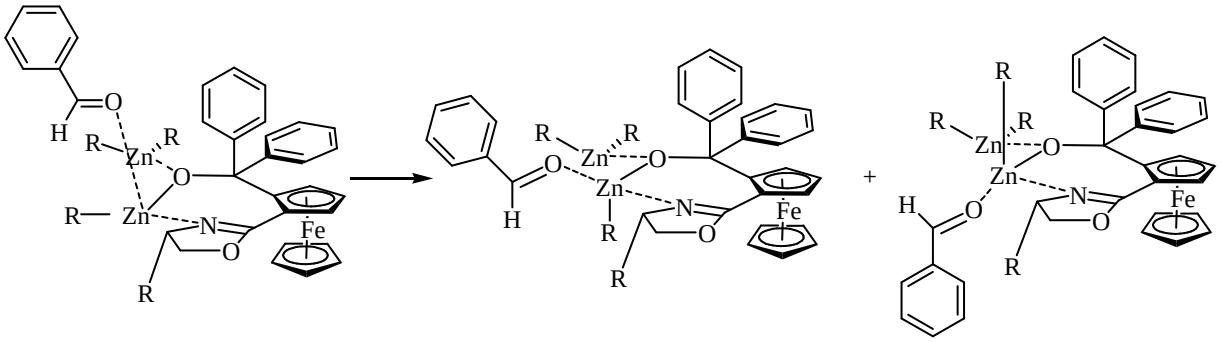


Figure 12. Proposed intermediates for the asymmetric alkylation of aldehydes by means of diorganozinc reagents catalyzed by hydroxymethylferrocenyloxazolines.

When sterically demanding ligands such as (*S,Rp*)-**128** or (*S,Rp*)-**129** are employed in combination with sterically demanding diorganozinc reagents (diaryl- or dialkynylzinc), the normal approach of the aldehyde might be hindered in some cases leading to no differentiation between intermediates **150** and **151** (the catalyst might be unable to discriminate between the *re*- and the *si*-side of the aldehyde).

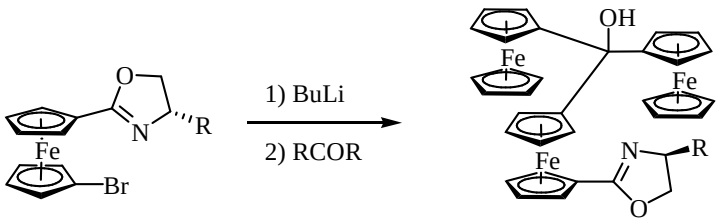
Nevertheless, it is also possible that the wrong combination of extreme bulk around the ferrocene backbone and a large diorganozinc reagent, might force the ligand into a different conformation. This possibly results in a different set of transition states as compared to the diethylzinc case, where no asymmetric induction is possible.

Both hypotheses might explain the different behaviour of ligands (*S,Rp*)-**128** and (*S,Rp*)-**129** in the ethyl-, aryl- and alkynylzinc addition to aldehydes.*

These results reveal the importance of well-balanced structural features of catalysts, as well as the right cooperative interactions between the substrate-reagent-catalyst system, for achieving high enantioselectivity.

* However, other explanation may be that the presence of unexpected π-π interactions, which might lead to a different transition state.

An interesting extension of this work will be the synthesis of triferrocenylmethane derivative (*S*)-**152** easily accessible from a bromoferrocenyloxazoline derivative (*S*)-**153** and diferrocenylketone (**40**). Such type of ferrocenyloxazolines (with the two coordinating groups situated in different cyclopentadienyl rings) have been proved to be effective catalysts in the asymmetric addition of diorganozinc reagents to aldehydes.[81]



(*S*)-**153**[81] (*S*)-**152**

Historically, development and discovery of catalysts have been an expensive process of trial and error. For a given reaction type, hundreds or thousands of candidate catalysts must be painstakingly developed and tested before a suitable catalyst is identified.

The combinatorial approach (already successfully applied in pharmaceutical research) to heterogeneous catalysis includes the preparation of a large number of catalytic materials and their screening by special adapted fast and high throughput techniques. Its aims at reducing considerably the time and cost for catalyst development and at enhancing the chance of finding new catalytic materials. The key issue in this approach is the development of appropriate techniques for fast synthesis, screening and selection of large numbers of catalysts.

Designing a catalyst from first principles based on the details of a reaction, a process known as rational design, would dramatically impact the field of catalysis because it could help eliminate most of the candidates that are unlikely to succeed, thus providing a substantial reduction in the cost of developing a new catalyst.

Rational design has been a long-standing goal of catalysis science, but realizing this vision has remained elusive. The here reported studies on the asymmetric alkylation of aldehydes by means of diorganozinc reagents catalyzed by hydroxymethylferrocenyloxazolines (*S,Rp*)-**128** and (*S,Rp*)-**129**, illustrated the difficulties encountered on this process. Even with a deep understanding of structure-activity relationships, the success of the proposed catalyst is not ensured.

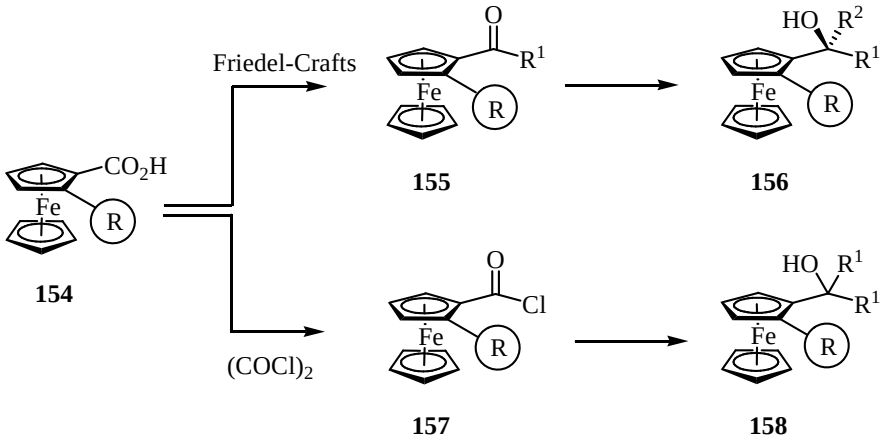
3.7 Chiral 1,2-Disubstituted Triferrocenylmethane Derivatives

The above discussed methodology for the synthesis of chiral triferrocenylmethane derivatives [*ortho*-lithiation of ferrocenyloxazolines followed by quenching with diferrocenylketone (**40**)], has a clear disadvantage in that it is suitable only for the synthesis of oxazoline derivatives. In order to overcome this limitation a novel route was sought.

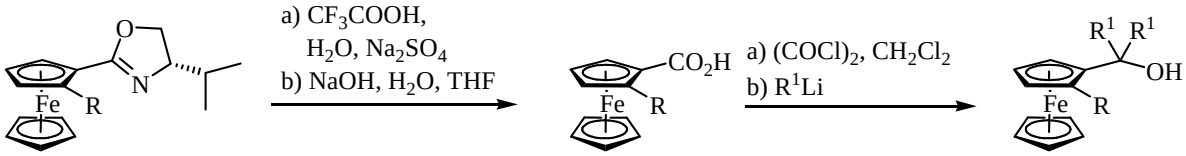
New methods for the practical asymmetric synthesis of 1,2-disubstituted ferrocene derivatives have recently received much attention. The general approach to this type of compounds involves a directed *ortho*-functionalization of ferrocene precursors bearing *ortho*-directing auxiliary groups. However, a major limitation in nearly all methods is that the *ortho* directing group of the substrate does usually not allow functional group modification and this limits the compounds that can be generated by this route.

In the case of the oxazolines, removal of the chiral auxiliary group involve a multireaction sequence: α-substituted ferrocenyloxazolines can be converted into the corresponding enantiomerically pure α-substituted ferrocenecarboxylic acids **154** by employing Meyers´s procedure[92] for transformations of the oxazolines.[79, 93]

It was reasoned that α -substituted ferrocenecarboxylic acids **154** would act as a versatile starting material for the synthesis of ferrocene ligands: Friedel-Crafts acylation followed by a diastereoselective addition would lead to unsymmetrical carbinols **156**. On the other hand, nucleophilic addition to the planar chiral ferrocenoyl halide **157** would give the carbinols **158**.

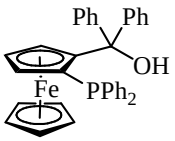


In a sequence identical to the one already described for the synthesis of 2-diphenylphosphinoferrocenecarboxylic acid (*Sp*)-(**162**),[93] planar chiral (*Rp*)-2-methylferrocenecarboxylic acid (**161**)[94] was obtained from the parent oxazoline (*S,Rp*)-**159**.

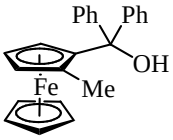


(*S,Rp*)-**159**[53 - 55] R = Me
(*S,Sp*)-**160**[53 - 55] R = PPh_2

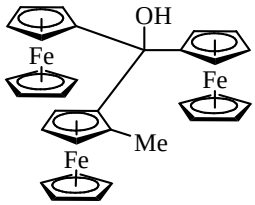
(*Rp*)-**161**[94] R = Me (49 %)
(*Sp*)-**162**[93] R = PPh_2 (72 %)



(*Sp*)-**163** (50 %)



(*Rp*)-**164** (35 %)



(*Rp*)-**165** (31 %)

Ferrocenoyl chlorides generated *in situ* from carboxylic acids (*Rp*)-**161** and (*Sp*)-**162**, were treated with an excess of phenyllithium or monometallated ferrocene to give the enantiomerically pure carbinols (*Sp*)-**163**, (*Rp*)-**164** and (*Rp*)-**165**.

The solid-state structure of carbinol (*Rp*)-**164** shows one equatorial phenyl group while the other phenyl substituent occupies an axial position with regard to the cyclopentadienyl backbone. The alcohol is oriented towards the iron due to an interaction of the hydrogen with the π-system of the unsubstituted cyclopentadienyl ring.

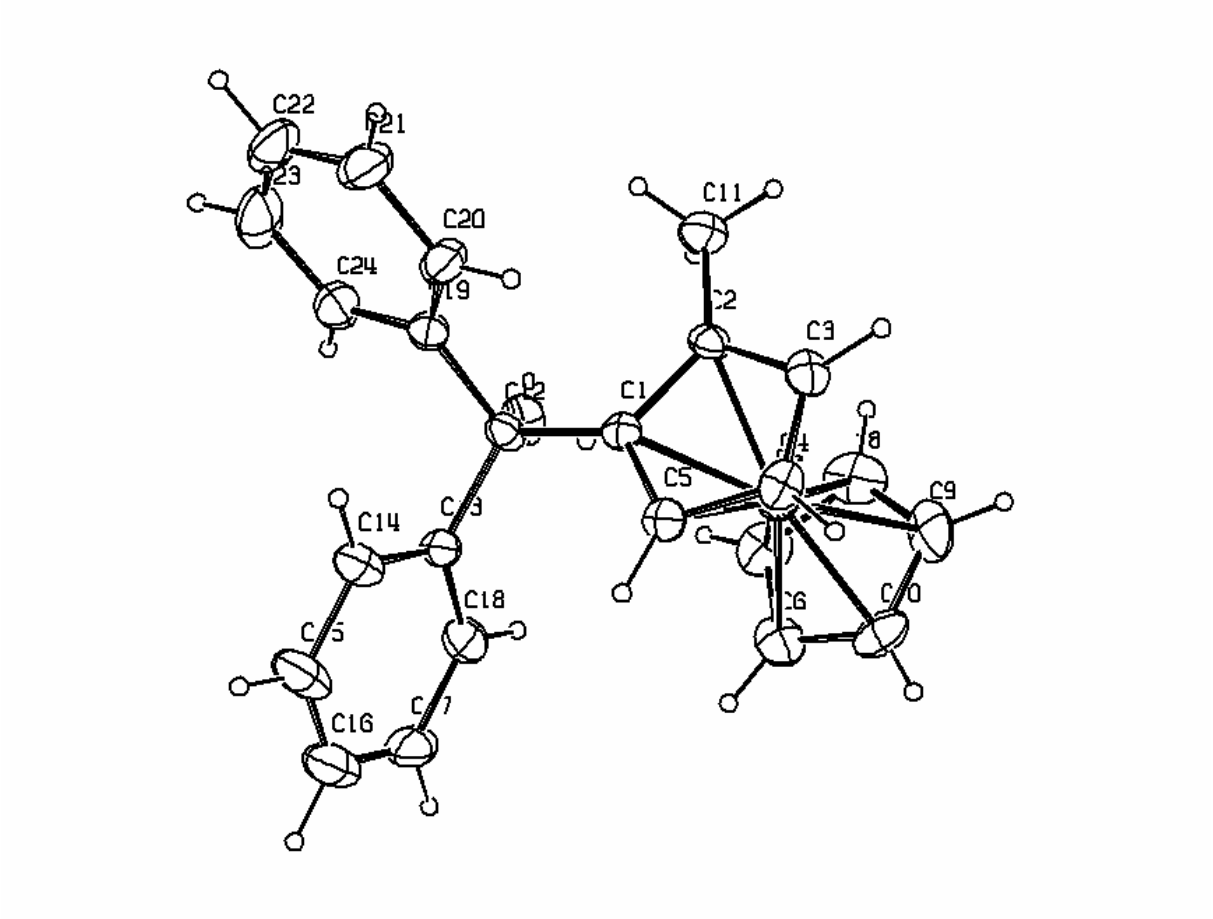
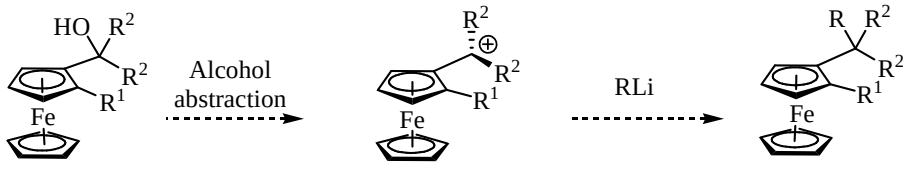


Fig. 13: ORTEP drawing of the structure of (*Rp*)-**164** in the crystal. Selected bond lengths [Å], angles [°] and dihedral angles [°]:C1-C12 1.514(5), C12-O 1.437(4), C12-C19 1.513(6), C12-C13 1.546(5), C2-C11 1.505(6), C3-C2-C11 124.6(5), C2-C1-C12 127.3(4), C5-C1-C12 125.8(4), C1-C12-C13 109.7(4), C19-C12-C1 111.6(3), C19-C12-C13 109.4(3), O-H 0.814(10), O-C12-C19 106.3(3), O-C12-C1 110.8(3), O-C12-C13 108.9(3), C12-O-H 104(3), C20-C19-C12 123.6(4), C24-C19-C12 118.2(5), C18-C13-C12 120.0(4), C14-C13-C12 122.2(4), C11-C2-C1-C12 –1.6, O-C12-C1-C2 57.4, C5-C1-C12-C13 –7.5, O-C12-C19-C24 43.7, C20-C19-C12-C1 –17.4, O-C12-C13-C8 35.5, C1-C12-C13-C18 –86.8, C1-C12-C13-C14 91.3, O-C12-C13-C14 –147.3.

Compounds **163 - 165** offer the possibility to prepare stabilized carbocations connected to a ferrocene system with planar chirality where isomerization (by rotation around the carbenium center) is not possible. This will allow the synthesis of chiral carbocations **166**.

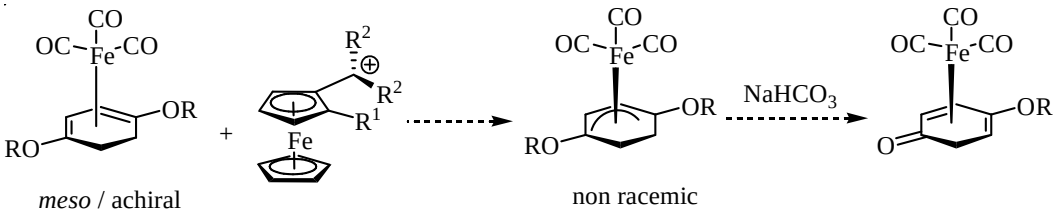


163 - 165 **166** R^1 = Me or PPh_2 **167**
R^2 = alkyl, aryl or Fc

Compounds **166** can be used to produce new chiral derivatives by nucleophilic addition, or can be directly used as chiral surrogates of the trityl cation **10** in the enantioselective hydride abstraction from organic substrates.[95]

Hydride transfer from an organic substrate to a cation is a fundamental oxidation mechanism in organic chemistry.[96] The majority of these reactions have utilised Ar_3C^+ **10** as the oxidant. The salts corresponding to [BF_4^-] and [PF_6^-], dehydrogenate various types of ethers and ketals to carbonyls compounds, convert enol ethers and enamines to enones, and are often used in conjunction with organometallic substrates to increase the *hapto* number of the metal atoms.

In principle, each of these processes could provide optically enriched chiral material by subjecting a particular *meso* or achiral substrate to oxidation with a chiral reagent.[95] Recently, the transformation shown in **Figure 14** has been reported using several chiral trityl species. We believe that using **166** higher enantioselectivities should be achievable.



meso / achiral non racemic

166 R^1 = Me, $SiMe_3$
R^2 = Ph, Fc

Figure 14. Enantioselective hydride abstraction in *meso* η^4-iron dienes.

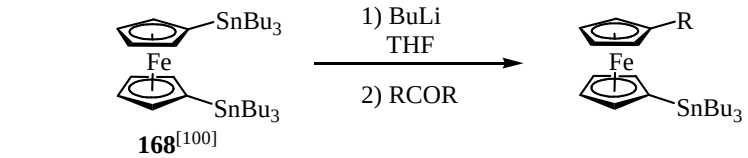
In compounds **166**, the capacity of hydride abstraction as well as the enantioselectivity of this event could be easily tuned by the choice of the substituents (R^1 and R^2).

3.8 1´-Substituted Triferrocenylmethane Derivatives

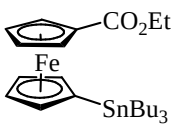
Due to its high stability and its versatility as starting material in the synthesis of useful compounds, ferrocene (**14**) plays a key role in many areas of research.[12] An important advantage of ferrocene containing complexes is that their electron-donor ability may be fine-tuned by the choice of number and nature of the substituents. Moreover, ferrocene derivatives, in which the two cyclopentadienyl rings bear different substituents receive considerable interest owing to their utility in the synthetic construction of large ferrocene based assemblies.

Thus, the synthesis of ferrocenes with tailor-made properties has been a goal for many synthetic chemists, and although, many useful synthetic methods have been published, most are applicable only in special cases. These methods involve either selective introduction of a second substituent in the 1'-position of a monosubstituted derivative or the selective transformations of one substituent of symmetrically disubstituted compounds. Such reactions require suitable functionality at the cyclopentadienyl ligands.

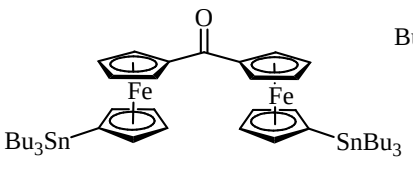
Stannyl substituents are particularly promising in this context as they are easily replaced by lithium after treatment with butyllithium. The transmetallation reaction of the tributylstannyl group, originally developed by Seyferth is a very clean and efficient method for the preparation of vinyl- and allyllithium compounds. This methodology has been recently extended to the stepwise transmetallation of the Cp rings of ferrocene (**14**), leading to new ferrocenyl ligands.[97-99]



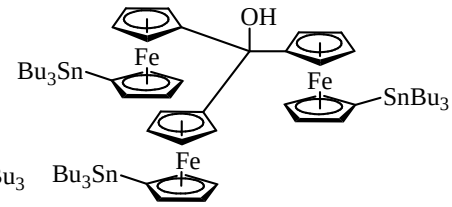
168[100]



169 (79 %)



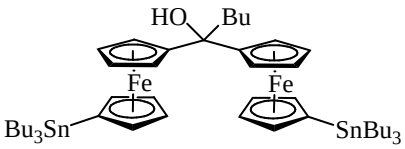
170 (55 %)



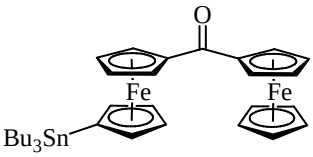
171 (75 %)

When 1,1'-bis(tributylstannyl)ferrocene (**168**)[100] was treated with 1 equiv. of butyllithium followed by 1 equiv. of ethyl chloroformate difunctionalized ferrocene **169** was obtained in 79 % yield. When under otherwise identical reaction conditions 0.5 equiv. of ethyl chloroformate was used, the diferrocenylketone **170** was isolated in 55 % yield. Finally, use of 0.33 equiv of ethyl chloroformate resulted in a 75 % yield of the tristannylated triferrocenylmethanol **171**.

In a brief assessment of the chemical properties of ketone **170** treatment with butyllithium resulted in the formation of alcohol **172** in 91 % yield. However, attempts to protect the keto group in **170** as an ethylene acetal failed. Treatment of **170** with ethylene glycol and a catalytic amount of *para*-toluenesulfonic acid resulted in partial destannylation with formation of **173** in 28 % yield.



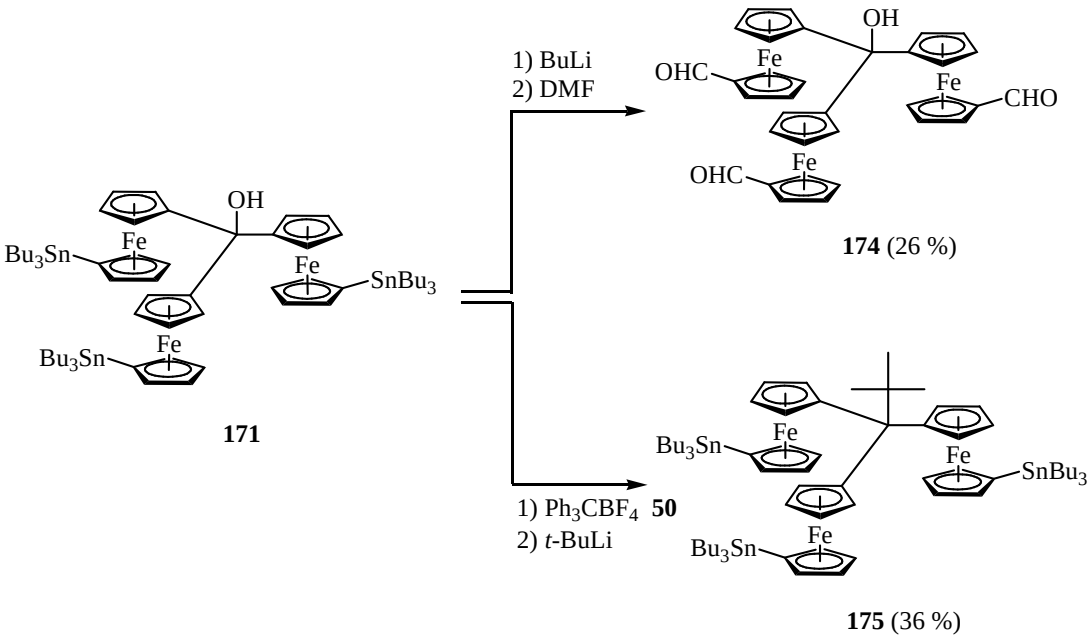
172



173

Compound **171** is the first triferrocenylmethane derivative with substituents at the cyclopentadienyl ligands opposite to the coupling ones. As a first test for the feasibility of a multiple transmetallation, **171** was treated with 6 equiv. of butyllithium followed by an excess of dimethylformamide (DMF). After aqueous work up the trialdehyde **174** was obtained as a red liquid in 26 % yield, which corresponds to an average yield of 64 % per formylation step. This clearly shows that a threefold transmetallation works.

Next, the hydroxy functional group in **171** was replaced by a sterically more bulky *tert*-butyl substituent. This was done by treatment of **171** with triphenylmethylcarbenium tetrafluoroborate (**50**) followed by 1.2 equiv. of *tert*-butyllithium. **175** was obtained in 36 % yield as a red liquid after column chromatography.



All the new compounds can be stored in the air for some time without any sign of decomposition. However, after some months a dark solid forms, which can easily be removed by filtration through silica gel.

3.9 Metallocenophanes

Metallocenophanes are ring systems in which the metallocene units are joined by an atomic or a molecular bridge. Metallocenophanes can be divided into two different classes:* [m]-metallocenophanes are those, where one metallocene nucleus is connected by one or more bridges between the two Cp rings; [m,m]-metallocenophanes are those where two or more metallocene nuclei are connected by one or more bridges.

* The nomenclature of metallocenophanes is derived from the system proposed by Smith and Vögtle *et al.* for naming bridged organic aromatic cyclophanes. All bridged metallocenes are referred to as "metallocenophanes". According to the IUPAC rules the position at which a metallocene may be substituted are numbered 1 to 5 on one cyclopentadienyl ring and then 1' to 5' on the second ring.

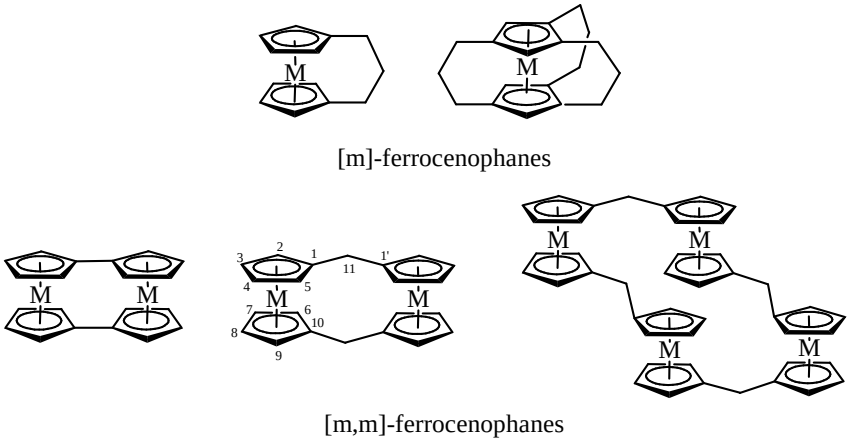


Figure 15. [m]- and [m,m]-ferrocenophanes.

Permutation of the size, type and number of bridge atoms, and of course, the metallocene metal itself, clearly give rise to questions regarding the structural integrity of metallocenophanes and the influence that the bridge can have on the chemistry of those molecules.[101, 102]

There have been many different classes of multinuclear ferrocenophanes reported in the past 30 years, and several reviews have documented these discoveries.[30, 101, 102] Most of the work has focused in ferrocenophanes derived from the cyclopentadienyl units of type **176**, **177**, **178** and **179**.

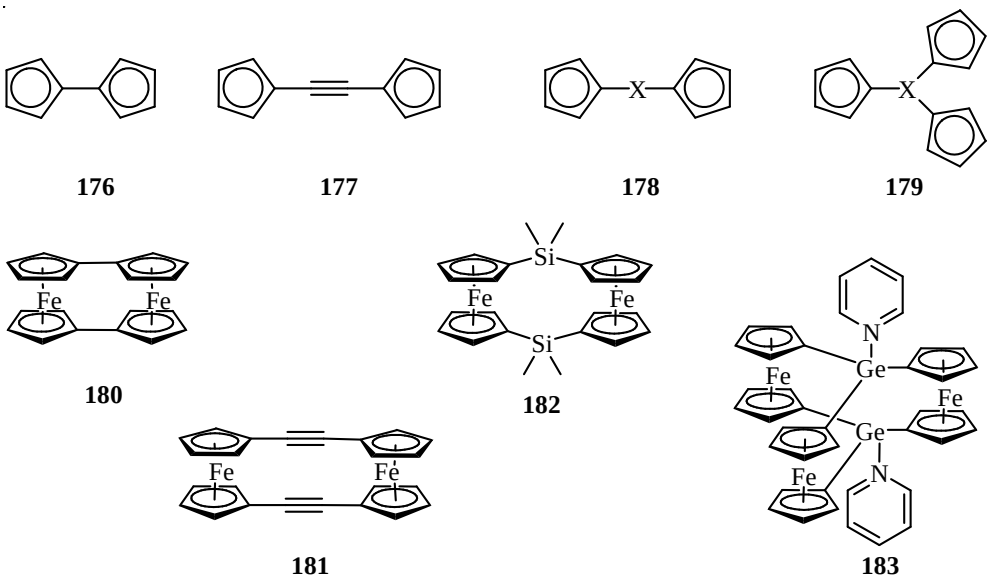


Figure 16. Some examples of [m,m]-ferrocenophanes.

To our knowledge, no example of trinuclear [1,1]-ferrocenophane of type **179** bridged by carbon atoms has been reported. However, a trinuclear ferrocenophane complex in which the three ferrocene-1,1'-diyl units are held together by gallium centers has already been described.[103]

Even though the large C-Ga distance (about 1.97 Å) in **183**,* the three ferrocenyl units deviate from a mutual coplanar arrangement to relieve the steric repulsion between the inner α-hydrogens. This results in the complex having a slightly twisted and thus chiral structure (the ferrocenyl units are tilted in the same direction relative to the Ga-Ga axis).

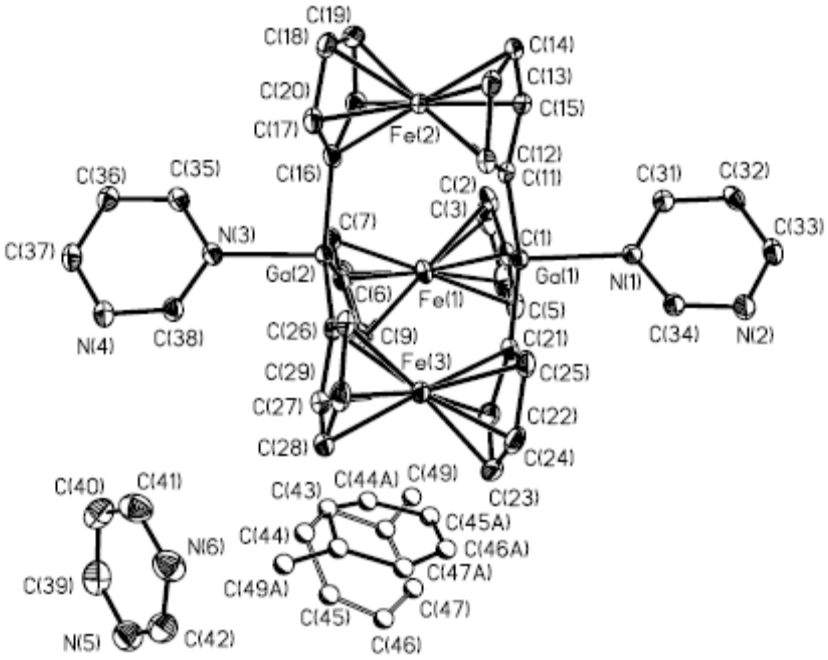


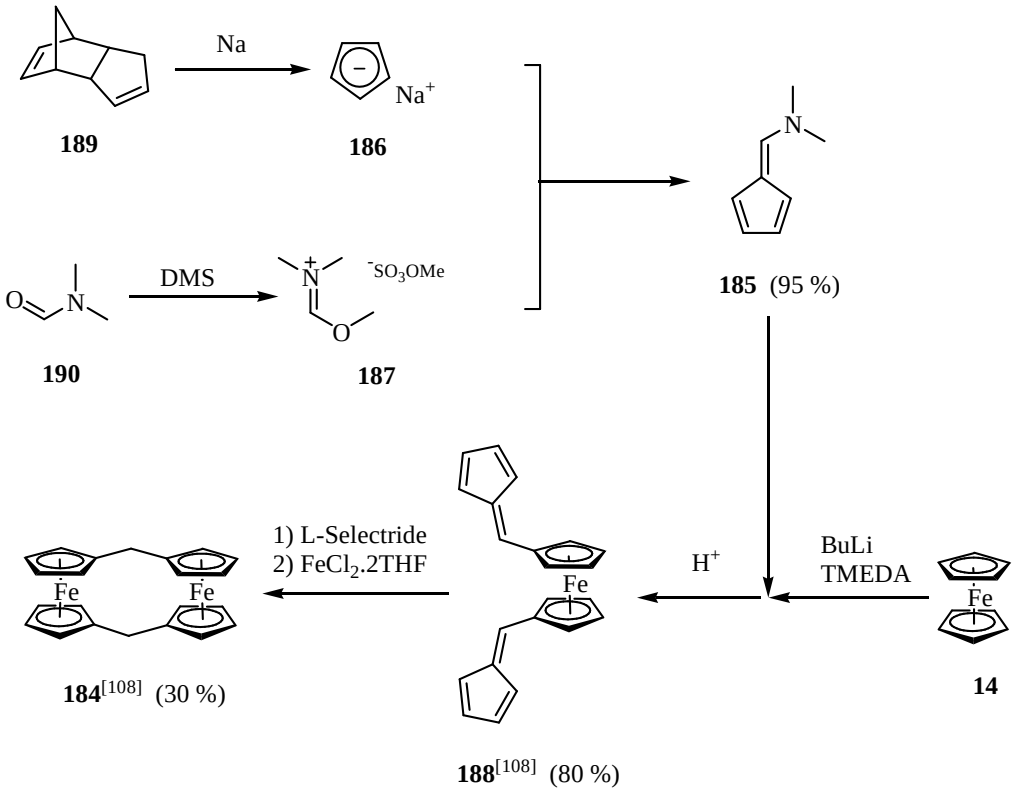
Fig. 17: structure of **183** in the crystal.[103]

* the C-CH_2 distance in [1,1]-ferrrocenophane (**184**) is about 1.50 Å

3.10 Synthesis of [1,1]-Ferrocenophane (184)

[1,1]-Ferrocenophane (**184**) in which two ferrocenes are linked together by two bridging methylene groups at the 1,1´-positions has been studied from several points of view. Aspects that have attracted interest include the isomerism and conformational flexibility possible in [1,1]-ferrocenophane derivatives,[102, 104] the unusually stable carbanions formed by the deprotonation at the methylene bridges of [1,1]-ferrocenophanes,[105, 106] the stable carbocation formed by hydride abstraction from the bridges of [1,1]-ferrocenophanes,[102] the utility of [1,1]-ferrocenophanes derivatives as hydrogen generation catalysts[107] and the intramolecular metal-metal interactions in mono- and dioxidized [1,1]-ferrocenophanes.[102]

[1,1]-Ferrocenophane (**184**) can be considered as a very useful starting material for the synthesis of more complex metallocenophanes. Up to this time, the best preparative method for **184** has been reported by Mueller-Westerhoff and relies on the facile conversion of fulvenes into cyclopentadienide salts and the reaction of the latters with metal halides to form the respective metallocenes.[18, 108]



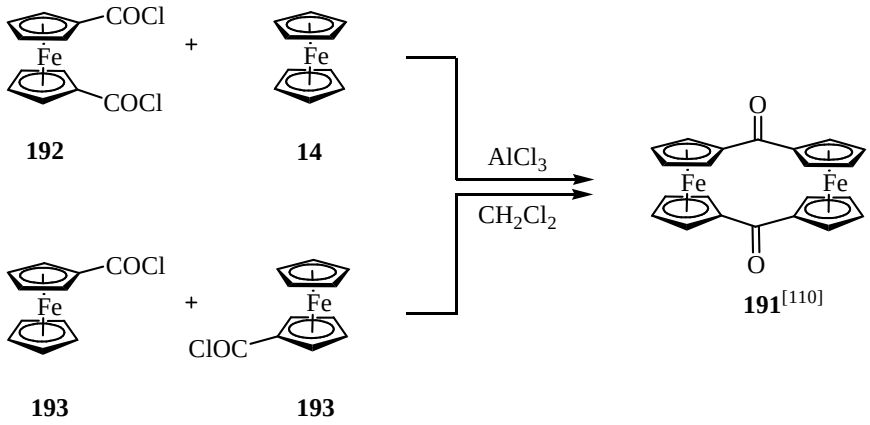
Double addition of 1,1´-dilithioferrocene TMEDA complex[109] to 6-(dimethylamino)-fulvene **185** [from the condensation of sodium cyclopentadienide (**186**) and *N*,*N*-dimethylformamide-dimethyl sulfate complex **187**] produces the deep blood-red 1,1´-bis(fulvenyl)ferrocene **188**. Reduction with L-selectride followed by complexation of the bis(cyclopentadienyl)methyl-ferrocene dianion with $FeCl_2$.2THF (under careful control of the reaction conditions), gave the yellow [1,1]-ferrocenophane (**184**) in moderate yield.[108]

Pure [1,1]-ferrocenophane (**184**) is stable in the solid state and stable in solution as long as air is excluded. In solution, oxidation to the mono- and diketone rapidly occurs.

3.11 [1,1]-Ferrocenophane-1,12-dione (191)

3.11.1 Synthesis of [1,1]-Ferrocenophane-1,12-dione (191)

The [1,1]-ferrocenophane-1,12-dione (**191**) was first prepared by an intramolecular Friedel-Crafts cyclization between 1,1´-bis(chlorocarbonyl)ferrocene (**192**) and ferrocene (**14**) or by self-condensation of ferrocenoyl chloride (**193**). This reaction is, however, poorly reproducible and low-yielding.[110]



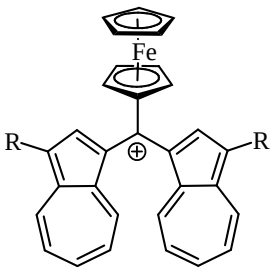
An alternative strategy involves the oxidation of [1,1]-ferrocenophane (**184**) by MnO_2 in benzene (**15**).[110] This oxidation has been reported to occur with great ease and has been used as a means to quantitatively convert **184** to [1,1]-ferrocenophane-1,12-dione (**191**).

Unfortunately, MnO_2 is known to be a capricious reagent, which needs careful control of the reaction conditions. In our hands, the oxidation of **184** never went to completition and most of the starting material was lost, supposedly adsorbed into the metal oxide.

The oxidation of benzylic positions to carbonyl groups is one of the most important transformations in synthetic chemistry and numerous methods have been developed involving various types of reagents (MnO_2, DDQ, PDC, CAN, IBX, *etc*).[111]

2,3-Dichloro-5,6-dicyano-1,4-benzoquinone or dichlorodicyanoquinone (DDQ) is a well-known dehydrogenating reagent which has been found a wide number of applications in steroid chemistry and in synthesis of complex natural products.[112] In the field of organometallic chemistry, it has mostly been used as one-electron oxidant for the synthesis of charge transfer complexes.

Noteworthy, is the DDQ mediated synthesis of azulenylferrocenylmethylcations **194** and **195** reported by Asao,[113] which prompted us to attempt the oxidation of **184** using DDQ as oxidant.



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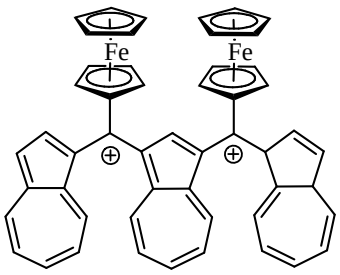
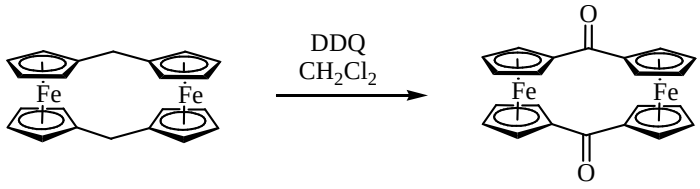


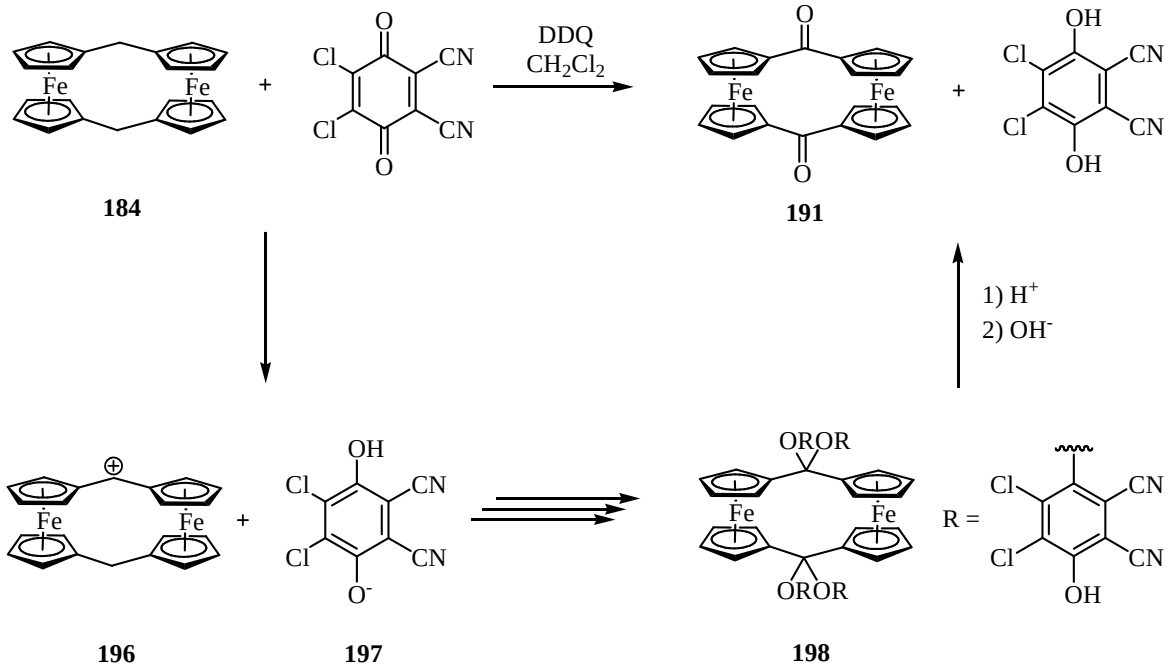
195

Consequently, an excess of DDQ smoothly effected the transformation furnishing the desired [1,1]-ferrocenophane-1,12-dione (**191**) in good yield.



184 **191** (76 %)

The reaction mechanism can be rationalised based on the strong hydride abstracting potential of DDQ. Oxidation of [1,1]-ferrocenophane (**184**) takes place by hydride transfer from the methyl bridge of **184** to DDQ, yielding the carbocation **196** and the hydroquinone anion **197** (presumably the feasibility of this reaction relies on the stabilization of the intermediate carbocation **196** as well as in the aromatization of the hydroquinone ring). Four fold abstractions, followed by hydrolysis of the presumed intermediate diacetal **198**, release the desired dione **191**.



184 **191** **196** **197** **198**

Figure 18. Proposed mechanism for the oxidation of [1,1]-ferrocenophane (**184**) mediated by 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ).

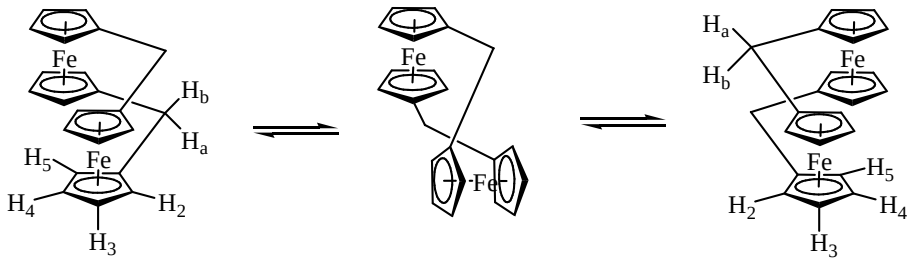
As expected,[114] the over-oxidation of [1,1]-ferrocenophane-1,12-dione (**191**) to the corresponding mixed-valence or dioxidized [1,1]-ferrocenophane species (Fe^{II} / Fe^{III} or Fe^{III} / Fe^{III}) did not take place.

[1,1]-Ferrocenophane derivatives can exist in two different conformations. The two bridges can sit on the same side (*syn*-form) or on the opposite sides of the two ferrocenyl units (*anti*-form). It is known that whether a [1,1]-ferrocenophane adopts either a *syn* or an *anti*-conformation depends on the balance of the two types of intramolecular steric repulsions in it. One is between the two bridging groups, which is only conceivable in a *syn* isomer. The other

is the repulsion between the two inner hydrogens at α- and α´-position. Molecular models demonstrate that the *anti* isomer is rigid and is not able to relieve the overcrowding, while the *syn* isomer is flexible and can easily twist to relieve all steric problems.[102]

Many types of [1,1]-ferrocenophanes bearing a variety of bridging groups have been synthesised and characterized by X-ray analysis. Among them, carbon (CH_2, CHMe, *etc.*) and heteroatom-bridged (BMe_2, $SnBu_2$, PPh, GaMe, *etc.*)[115] examples have been reported to adopt either a *syn*- or an *anti*-conformation depending on the aforementioned factors. Nevertheless, carbon-bridged [1,1]-ferrocenophanes have generally been assumed to have *syn* structures,* since *anti* isomers have been considered to be too strained.[102, 116-118]

The flexibility of the *syn* isomers has been proposed to be directly linked to the ease with which the two cyclopentadienyl ligands can rotate with respect to each other, although this motion is now coupled owing to the methylene bridges. This degree of freedom allows the molecule to undergo a synchronized motion in solution from one syn_A conformation to its mirror image (syn_B).



syn$_A$-**184** *syn*$_B$-**184**

Figure 19. Proposed isomerization of [1,1]-ferrocenophane (**184**).[102]

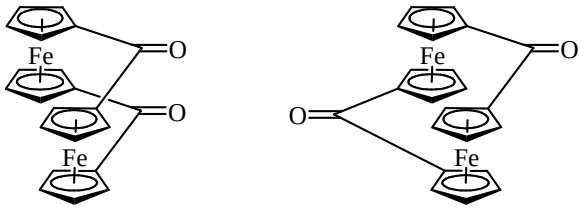
* The conformational and configurational nature of substituted CR_2-bridged [1,1]-ferrocenophanes have been discussed ever since 1,12-dimethyl-[1,1]-ferrocenophane (**199**) was synthesised. One of the original issues was if bridged substituted [1,1]-ferrocenophanes preferred the "flexible" *syn* conformation or the "rigid" *anti* conformation. For a long time, the *anti* conformation was ruled out due to the allegated inability to relieve internal steric strain.

The discovery that 1,12-dimethyl-[1,1]-ferrocenophane (**199**) may crystallize as an *anti* isomer[116] raised again the question of whether [1,1]-ferrocenophanes prefer *anti* or *syn* conformations in solution. However, NMR studies clearly pointed out that in solution carbon bridged [1,1]-ferrocenophanes might prefer a *syn* conformation indeed.[118]

The syn_A-syn_B isomerization of [1,1]-ferrocenophanes results in the "exchange" of the *exo*- and *endo*-positions as well as the α- and β-positions.

This dynamic behaviour becomes apparent from the unusual simplicity of the ^{1}H NMR spectra of [1,1]-ferrocenophanes. For example, the spectra of the parent [1,1]-ferrocenophane (**184**) shows a sharp singlet for the bridge methylene protons and a two multiplet structure for the ring protons (the eight protons in 2- and 5-positions and the eight protons in 3- and 4-positions each give rise to only one multiplet).

Similar to all the other [1,1]-ferrocenophanes, two different conformations might exist in [1,1]-ferrocenophane-1,12-dione (**191**). The two keto groups can sit on the same side (*syn*-form) or on the opposite sides of the two bridged ferrocenes (*anti*-form).



syn-**191** *anti*-**191**

On the basis of dynamic ^{1}H NMR studies a *syn*-conformation has been proposed for [1,1]-ferrocenophane-1,12-dione (**191**)[119] but until now, no solid state structural information has been given to confirm or reject this proposal.

Recrystallization of [1,1]-ferrocenophane-1,12-dione (**191**) from chloroform / hexane gave traces of a material suitable for the crystal structure analyse. Two different molecules were detected during the X-ray measurement, one of them carrying a center of inversion. Unfortunately, it was only possible to solve the structure of the *syn*-conformer.

In contrast to other [1,1]-ferrocenophanes were the ferrocenyl units are twisted to alleviate the steric repulsion between the inner protons,[104] the [1,1]-ferrocenophane-1,12-dione (**191**) adopts a *quasi*-perfect coplanar structure. The two cyclopentadienyl rings of the ferrocene moieties are eclipsed and parallel to each other. From the structural data the distance between the inner α-protons [3,(3´, 8, 8´)-H] can be calculated to be approximately 2.088 Å, shorter than the sum of Van der Waals radii of two hydrogen atoms.

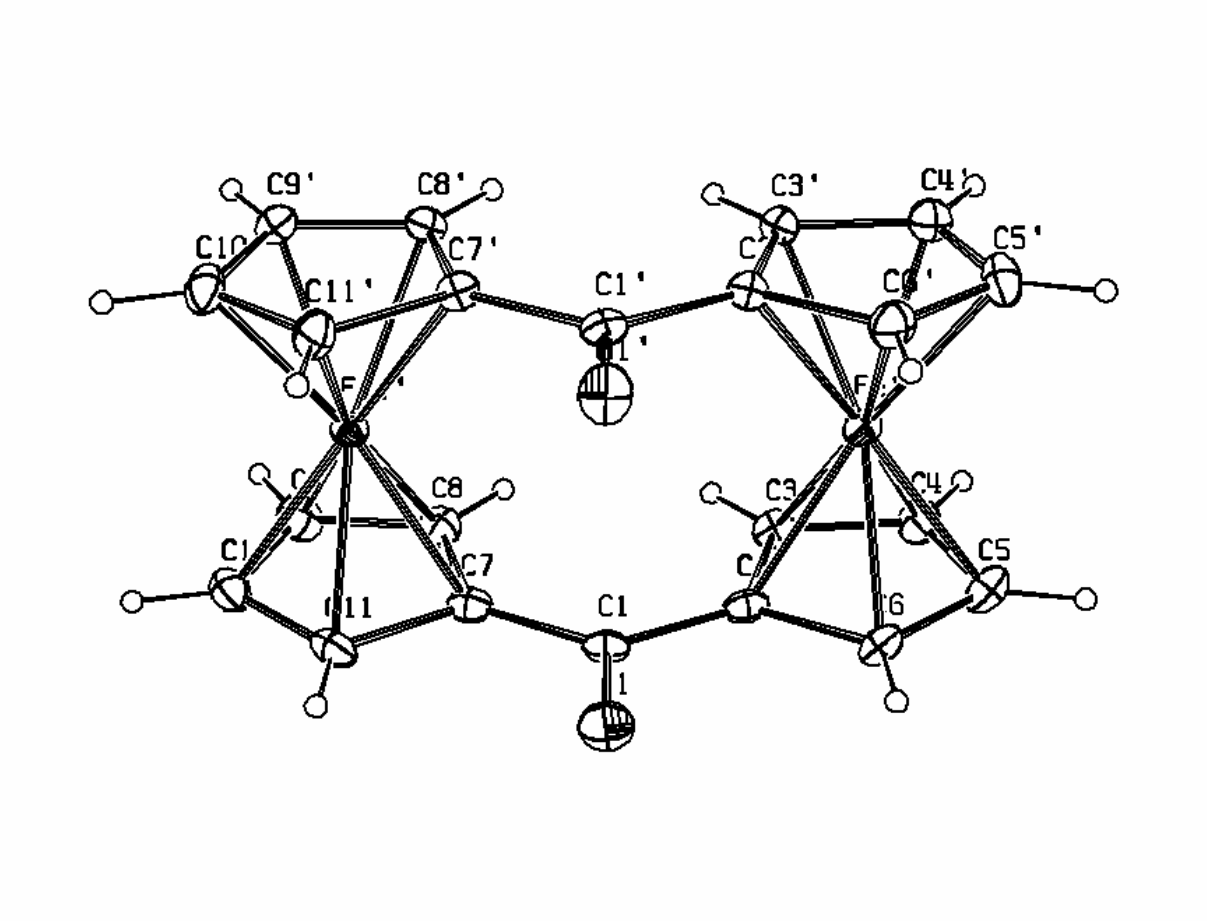


Fig. 20: ORTEP drawing of the structure of **191** in the crystal. Selected bond lengths [Å], angles [°] and dihedral angles [°]:O1-C1 1.235(9), O1'-C1' 1.215(8), C1-C7 1.479(10), C1-C2 1.484(10), C1'-C2' 1.481(9), C1'-C7' 1.490(9), O1-C1-C7 118.9(7), O1-C1-C2 117.5(6), C7-C1-C2 123.6(7), O1'-C1'-C2' 118.8(6), O1'-C1'-C7' 118.7(6), C2'-C1'-C7' 122.5(7), H3-H8 2.081, H3´-H8´ 2.109, C3-C2-C1-C7 – 0.4, C8-C7-C1-C2 – 1.4, C11-C7-C1-O1 1.8, C6-C5-C2-C1 – 3.5, C3´-C2´-C1´-C7´ – 0.5, C8´-C7´-C1´-C2´ – 0.4, C11´-C7´-C1´-O1´ – 1.3, C6´-C5´-C2´-C1´ – 2.0.

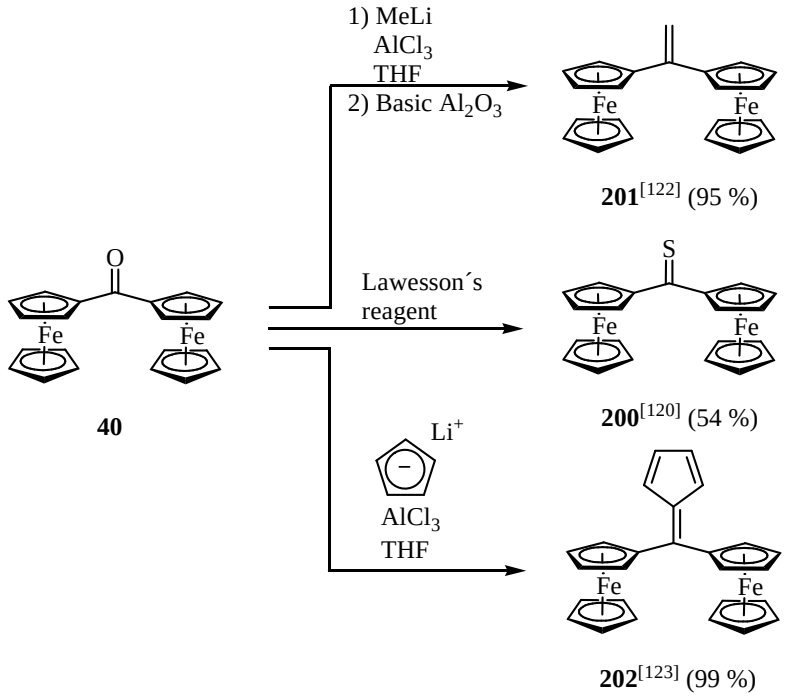
3.11.2 Reactivity of Diferrocenylketone (40)

The chemistry of [1,1]-ferrocenophane-1,12-dione (**191**) has hardly been explored because of its low yielding synthesis and its poor solubility in the organic solvents. In order to learn more about its chemistry, diferrocenylketone (**40**) has been used as a model to bring out the differences and resemblances between both systems.

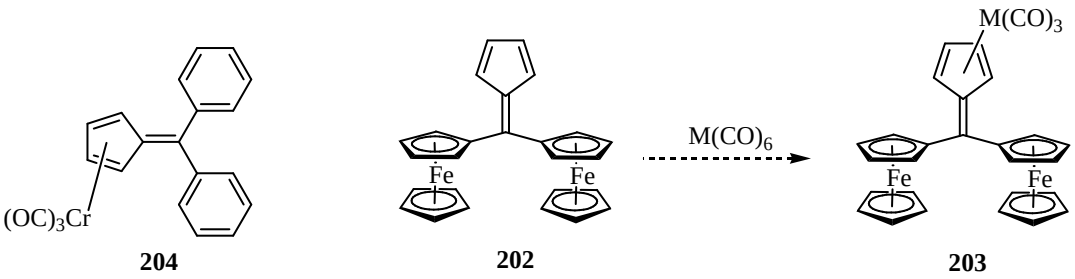
In a modification of a literature procedure,[120] diferrocenylketone (**40**) could be thionated with Lawesson´s reagent[121] under conventional reaction conditions to give diferrocenyl-thioketone (**200**) as violet crystals.

Moreover addition of MeLi or lithium cyclopentadienide in the presence of $AlCl_3$, followed by dehydrative treatment with basic aluminum oxide proceed smoothly to give **201**[122] and **202**[123] respectively.

Aromatic ketones, in which one or two of the aromatic substituents are part of a metallocene moiety, constitute the most unfavourable case for these condensation reactions due to the electron donating properties of the metallocene groups and because of steric hindrance by the cyclopentadienylmetal units. Aluminum chloride is a highly activating Lewis acid for reactions with oxygen containing substrates; formation of the thermodynamically very stable Al-O-Al bond allows the efficient conversion of a carbonyl functionality.



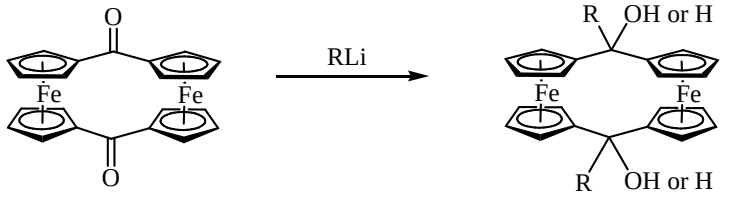
Fulvene **202** might be seen as a valuable intermediate for the synthesis of trimetallic species such as **203**. Complexation with $M(CO)_6$, similarly as in tricarbonyl(fulvene)chromium complexes as **204**,[124, 125] offers a general route to a new range of heterometallic complexes **203** (M = Cr, Mo, *etc*) which might exhibit electronic interactions between their metal centers.



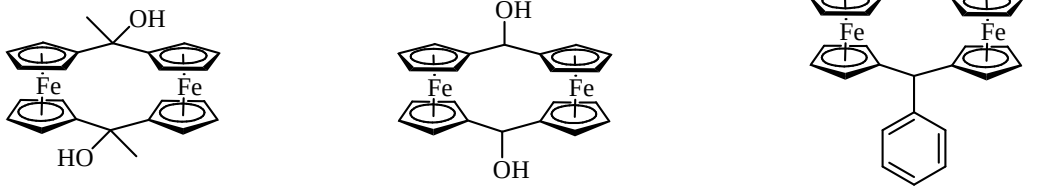
204 **202** **203**

3.11.3 Reactivity of [1,1]-Ferrocenophane-1,12-dione (191)

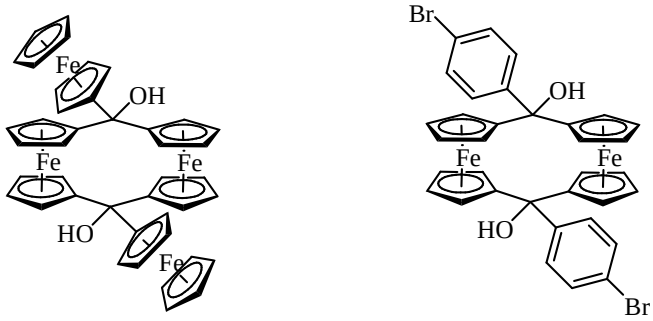
Pure 1,12-dione (**191**) was treated with a number of lithium reagents to give some known as well as some unknown bridged disubstituted [1,1]-ferrocenophane derivatives.



191



exo,exo-**206**[110] (87 %) *exo,endo*- and *exo,exo*-**205**[110] (50 %) *exo,exo*-**207**[110] (39 %)

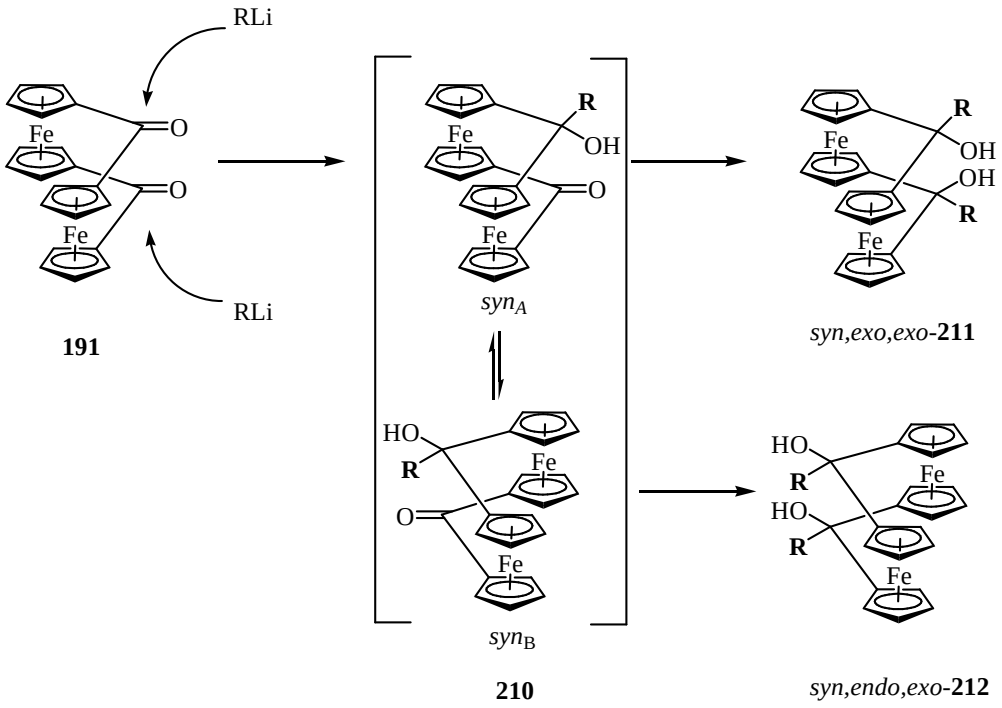


exo,exo-**209** (73%) *exo,exo*-**208** (98 %)

The reaction with lithium aluminum hydride gave a 2:1 mixture of *endo,exo*- and *exo,exo*-[1,1]-ferrocenophane-1,12-diol (**205**).[110] The reaction with methyllithium in the presence of $AlCl_3$ afforded *exo,exo*-1,12-dimethyl-[1,1]-ferrocenophane-1,12-diol (**206**).[110] Treating **191** with phenyllithium followed by treatment with $LiAlH_4$ resulted in *exo,exo*-1,12-diphenyl-[1,1]-ferrocenophane (**207**),[110] and the reaction with 4-bromophenyllithium gave *exo,exo*-1,12-di-(4-bromophenyl)-[1,1]-ferrocenophane-1,12-diol (**208**). *Exo,exo*-1,12-diferrocenyl-[1,1]-ferrocenophane-1,12-diol (**209**) was obtained by treatment of **191** with a large excess of dilithiumferrocene TMEDA complex.[109]

All new compounds are air-stable solids that give the expected analytical and spectroscopic data. Some of them were isolated as a mixture of isomers whereas others were isolated as a single diastereoisomer.

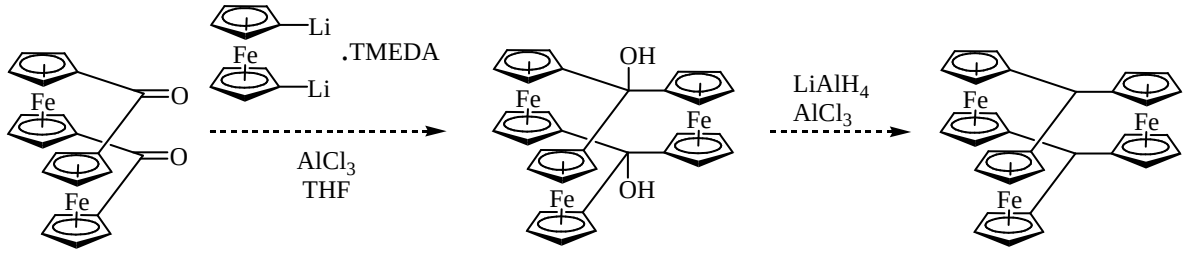
The nucleophilic addition to the keto function in [1,1]-ferrocenophane-1,12-dione (**191**) is expected to occur from the less hindered face. Owing to the preferred *syn* conformation of carbon bridged [1,1]-ferrocenophanes in solution, the *exo,exo* isomer is anticipated to be the only product of the reaction and therefore it has been proposed for compounds **206**, **207**, **208** and **209**.



However, [1,1]-ferrocenophane-1,12-diol (**205**) has been isolated as a mixture of stereoisomers (*exo,exo* and *exo,endo*). This might be explained on the bases of a syn_A-syn_B exchange equilibrium in intermediate **210**.[119] Depending on at which conformer the second nucleophilic attack occurs, an *exo,exo*-**211** or an *exo,endo*-**212** isomer might be obtained.

Derivatives with large substituents at the bridge will hamper the syn_A-syn_B exchange at **210**, favouring the *exo,exo* product (*e.g.* **206**, **207**, **208** and **209**), whereas derivatives with small substituents offer little steric hindrance to a syn_A-syn_B interconversion, and isomeric mixtures can be obtained (*e.g* **205**).

One of the possible products of the addition of 1,1´-dilithioferrocene TMEDA complex[109] to [1,1]-ferrocenophane-1,12-dione (**191**) is diol **213** which upon reduction might give the desired trinuclear ferrocenophane **34**.

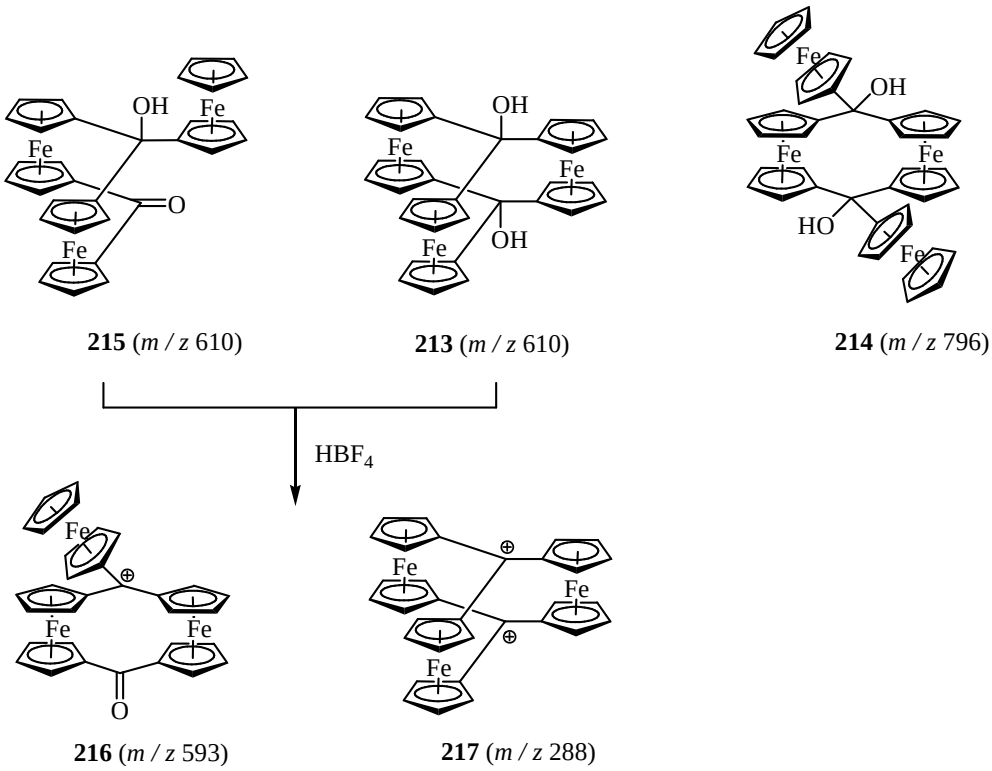


191 **213** **34**

In order to explore this possibility, the addition of 1,1´-dilithioferrocene TMEDA complex[109] to dione **191** was carried out under diluted conditions (c = 5 x 10^{-4} M) to favour the mono addition. The composition of the reaction mixture was investigated by mass spectroscopy.

In the MS(ESI^+) spectra two ion peaks, at 796 and 610 mass units, attracted our attention. The first one corresponds to the double addition product **214** (*m / z* 796). The second one might correspond either to the desired diol **213** or to the keto-alcohol **215**, which are constitutional isomers (*m / z* 610).

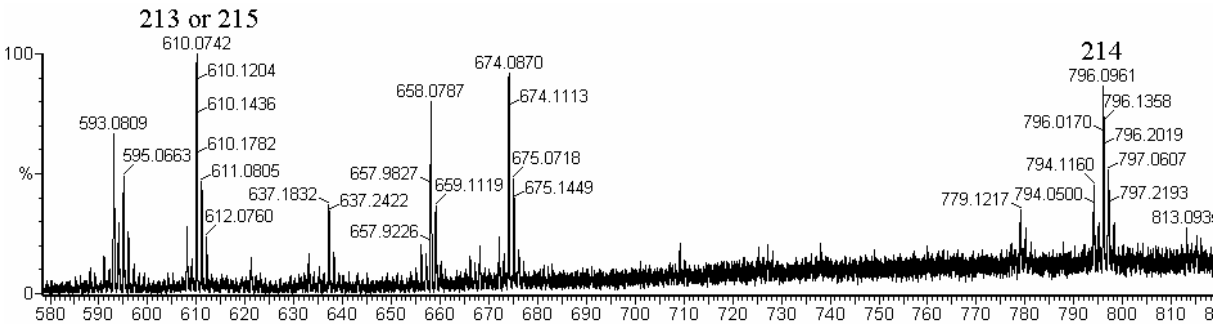
To distinguish between both of them, the reaction mixture was treated with HBF_4. Dehydrative treatment with acid of compounds **213** and **215** might lead to two different carbocations **216** (*m / z* 593) or **217** (*m / z* 288) respectively.



215 (*m* / *z* 610) **213** (*m* / *z* 610) **214** (*m* / *z* 796)

216 (*m* / *z* 593) **217** (*m* / *z* 288)

a)



b)

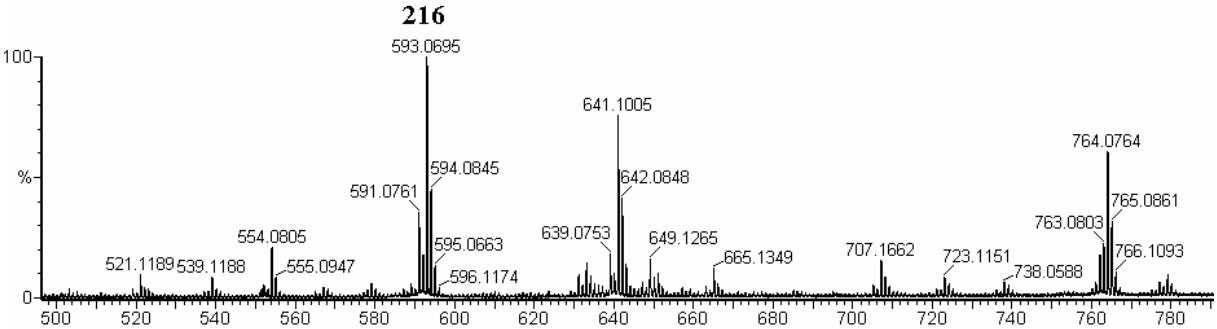
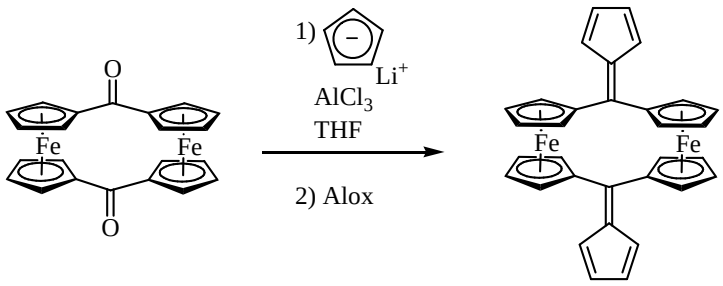


Figure 21. MS(ESI$^+$) spectra.. a) Reaction mixture. b) Reaction mixture after addition of an excess of HBF_4.

The ESI spectra of the reaction mixture after the addition of HBF_4, clearly shows that the mass at 610 belongs to compound **215**.

3.12 Synthesis of 1,12-Dicyclopentadienylidene-[1,1]-ferrocenophane (218)

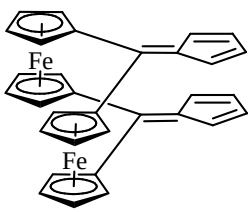
Addition of lithium cyclopentadienide to [1,1]-ferrocenophane-1,12-dione (**191**) with the previously optimized reaction conditions, resulted in difulvene **218** which was isolated after column chromatography as a red-black liquid that gave the expected analytical and spectroscopic data.



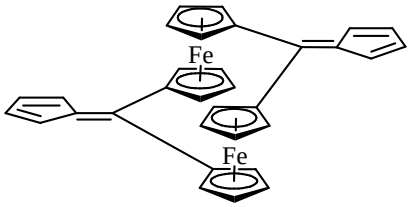
191 **218** (98 %)

As [1,1]-ferrocenophane-1,12-dione (**191**), 1,12-dicyclopentadienylidene-[1,1]-ferrocenophane (**218**) might exist in two different conformations (the *syn*- and the *anti*-form).

The conformational flexibility of **218** becomes clear in its ^1H NMR spectrum, which exhibits peaks for only two types of protons: the eight protons in 2- and 5-positions and the eight protons in 3- and 4-positions of the ferrocenyl units, give rise to only one multiplet each (the α and the β protons of the ferrocenyl units in the *syn*-isomer are inequivalent, however the syn_A-syn_B exchange renders them equivalent in the NMR time scale).



syn-**218**



anti-**218**

We investigated the temperature dependence of this spectrum in order to obtain an estimate for the barrier to the syn_A-syn_B exchange. The average spectrum was observed at room temperature (298 K). The eight ring protons of **218** are observed as two signals at $\delta = 4.54$ and 4.99 ppm and the eight protons of the fulvene ring as two signals at $\delta = 6.3$ and 6.4 ppm. Upon cooling, signals broadened until 192 K where the signal at 4.99 ppm coalesced to give two separate signals at 4.9 and 4.6 ppm (1977.21 and 1835.37 Hz).

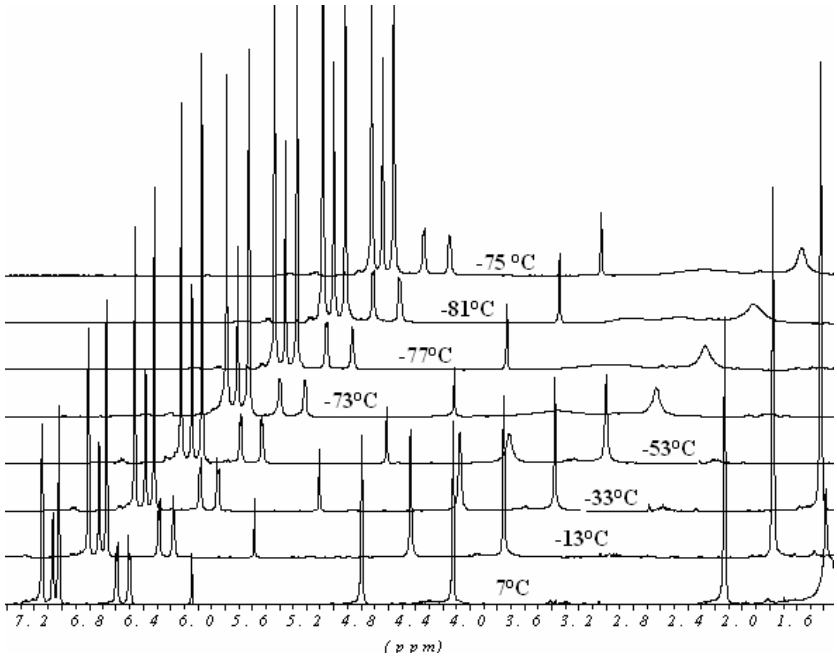


Figure 22. Low temperature ^{1}H NMR (500.1 MHz) spectra of 1,12-dicyclopentadienylidene-[1,1]-ferrocenophane (**218**) in d[8]-toluol.

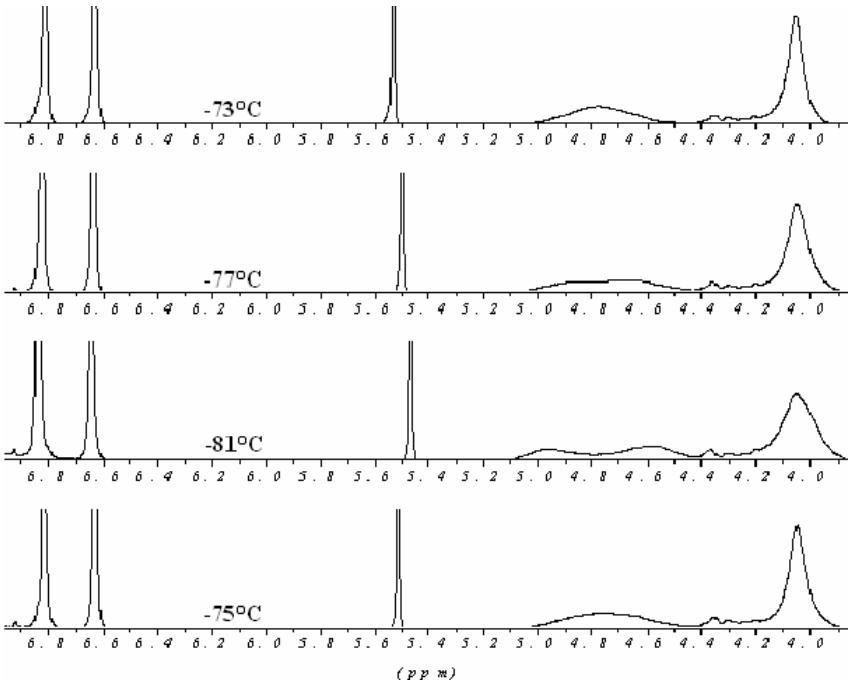


Figure 23. Low temperature ^{1}H NMR (500.1 MHz) spectra of 1,12-dicyclopentadienylidene-[1,1]-ferrocenophane (**218**) in d[8]-toluol.

The activation energy ($\Delta G^{\ddagger}$) of the dynamic process for the conformational change of **218** was calculated from the coalescence temperature ($T_c \pm 192$ K) of the ring protons signals in **218**, to be ± 38 kJ / mol, whose value is somewhat smaller than that ($\Delta G^{\ddagger}$ = 60 kJ / mol, T_c = 285 K)[119] of [1,1]-ferrocenophane-1,12-dione (**191**). The rate constant of the motion is estimated to be 3.2 x 10^{-3} s^{-1} at T_c.

The value of the activation energy at T_c was calculated from the equation $\Delta G^{\ddagger}(T_c) = 2.303\ RT_c\ (10.319 + \log \tau + \log T_c)$. R = 8.314 J K^{-1} mol^{-1}. The lifetime (τ / s) of the motion at T_c is estimated from the equation $\tau = 2^{1/2}\ \delta^{-1}\ \pi^{-1}$, where δ (Hz) is the difference in the chemical shift between the signals at the 2- and 5-positions.[119]

Cyclic voltammetry has been proven to be a powerful tool in order to investigate the electronic communication between transition metals with connecting ligand π-systems. Electrochemical techniques have been the mostly widely used tools to investigate metal-metal interactions in metallocene systems.

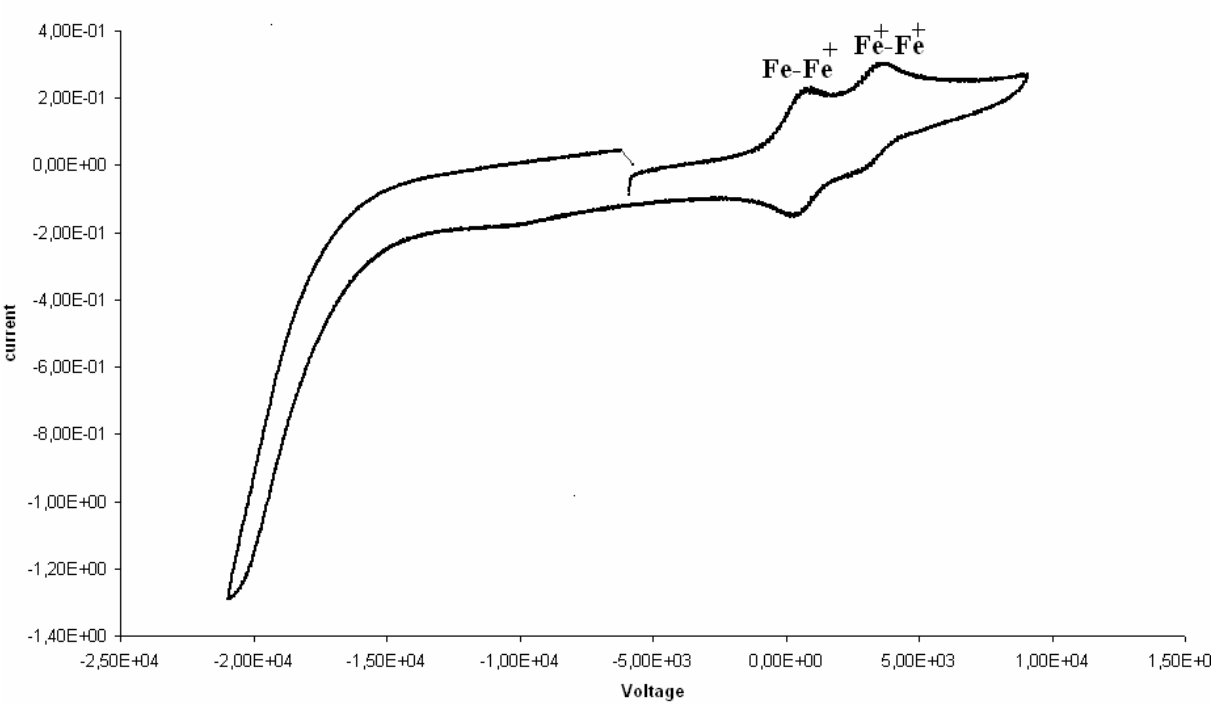


Figure 24. Cyclic Voltametry plot of 1,12-dicyclopentadienylidene-[1,1]-ferrocenophane (**218**), υ = 2 V / s, T = 25 °C, c = 0.5 mmol / L, c_{TBAHFP} = 0.2 mol / L, in CH_3CN relative to FcH / FcH^+.

E_a [mV]	i_a	E_k [mV]	i_k	ΔE [mV]	$E_{1/2}$ [mV]	i_a/i_k	υ [V / s]	$i_k/\upsilon^{1/2}$
94.5	$2.32\ 10^{-7}$	32.5	$-1.53\ 10^{-7}$	63.5	56.5	1.5	2	$1.08\ 10^{-7}$
357.5	$3.06\ 10^{-7}$	258.5	$-2.7\ 10^{-8}$	99	308	13.3	2	$1.9\ 10^{-8}$

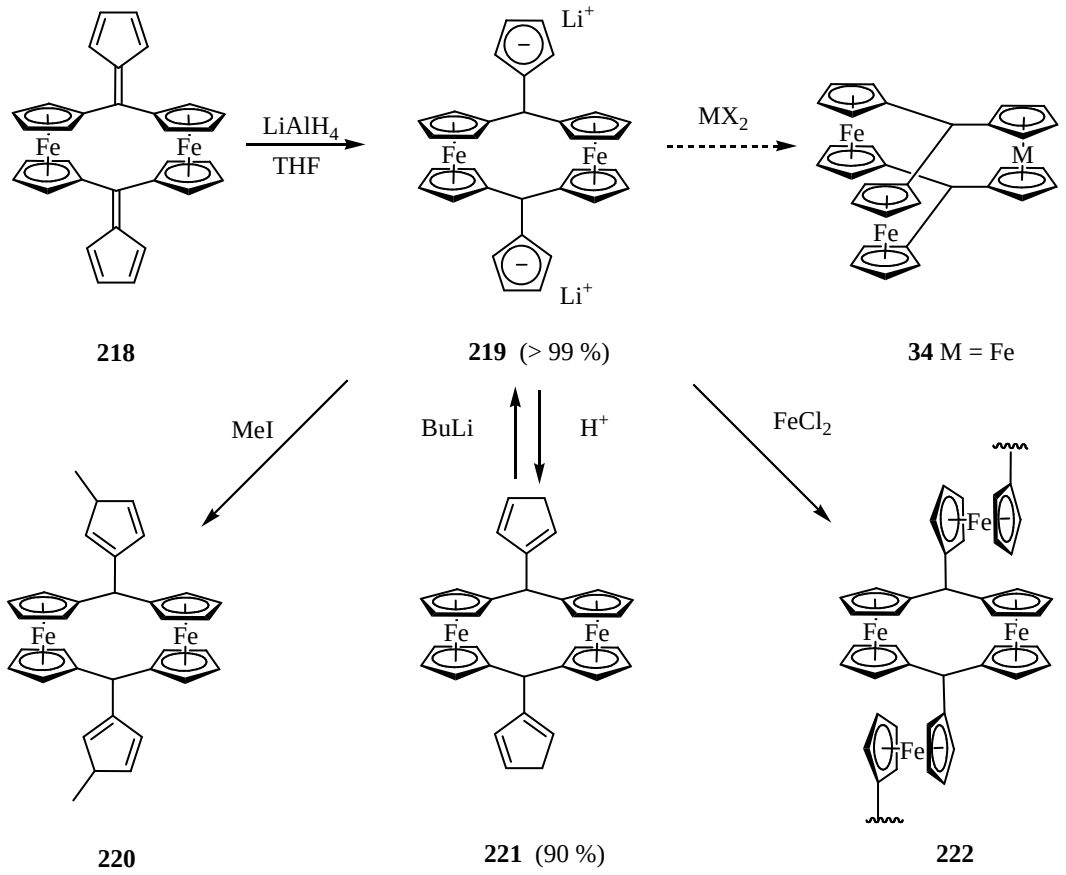
Table 4. Cyclic Voltammetry data for 1,12-dicyclopentadienylidene-[1,1]-ferrocenophane (**218**), υ = 2 V / s, T = 25 °C, c = 0.5 mmol / L, c_{TBAHFP} = 0.2 mol / L, in CH_3CN relative to FcH / FcH^+.

The cyclic voltammogram of 1,12-dicyclopentadienylidene-[1,1]-ferrocenophane (**218**) in acetonitril exhibits two reversibles waves at 94.5 and 357.5 V relative to the ferrocenium / ferrocene (**14**) couple. These waves can be assigned to successive redox events at each iron center.

3.13 Synthesis of Trimetallic Ferrocenophane (34)

The reaction of fulvenes with a variety of nucleophiles, bases, and reducing agents allow the preparation of many substituted cyclopentadienyl anions. The reaction of the latters with metal halides form the respective metallocenes.[18] We planned to exploit some of these reactions to synthesise the trimetallocene molecule **34** starting from 1,12-dicyclopentadienylidene-[1,1]-ferrocenophane (**218**).

The advantage of this synthetic route is that two ferrocenyl units and the entire carbon skeleton of the final product already exist in the precursor. Moreover, the proposed pathway might offer a useful entry to metallocenophanes with different metals.



218 **219** (> 99 %) **34** M = Fe

220 **221** (90 %) **222**

Conversion of the 1,12-dicyclopentadienylidene-[1,1]-ferrocenophane (**218**) into the dicyclopentadienide **221** was best achieved by using an excess of lithium aluminum hydride

in THF. This leads to an 1:1 mixture of *endo,exo*- and *exo,exo*-1,12-di(5-cyclopenta-1,3-dienyl)-[1,1]-ferrocenophane (**221**).*

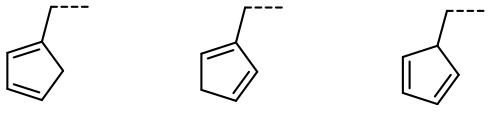
Deprotonation of dicyclopentadienide **221** with BuLi gave the dilithium salt **219** which was characterized by its reaction with MeI to give di(5-methylcyclopentadienide) derivate **220**. Compound **220** was not isolated but its existence was confirmed from the reaction mixture by mass spectrometry.

The reaction of diluted THF solution of dilithium salt **219** with $FeCl_2$.2THF gave in all cases polymeric material **222** which we were unable to characterize due to its low solubility in organic solvents. This oligomeric material might rise from the intermolecular reaction and shows the low probability of attainment of a transition state were the metal iron atom laid between the two cyclopentadienyl rings of **219**.

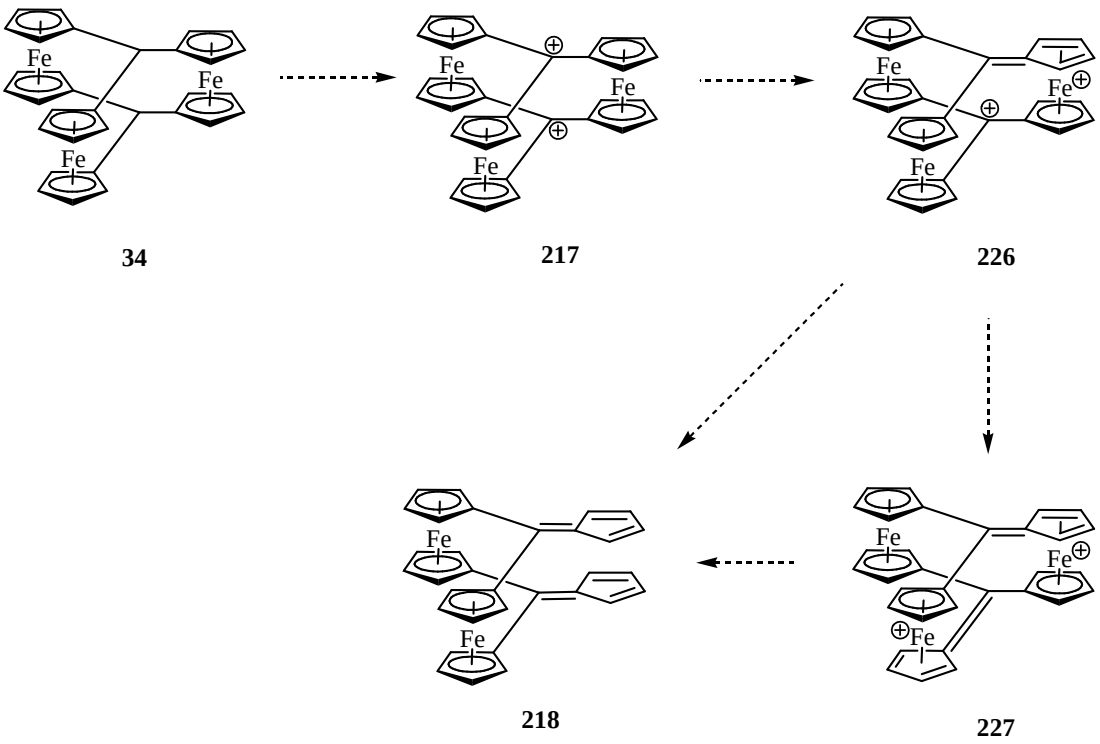
It has been suggested that a carbocation neighbouring a ferrocenyl unit might be seen as a neutral fulvene ligand coordinated in a η^6-fashion to a $(C_5H_5)Fe^+$ moiety. The nature of "ferrocenylcarbenium ions" as pentafulvene complexes has been postulated by the ease with which they are converted to uncomplexed pentafulvene.[125]

In trinuclear metallocene (**34**) a bridged "sp^2" hybridized carbocation **226** might be favoured due to the structural sterical demand of the system (the three ferrocenyl units might be fixed in a mutually coplanar geometry where a planar bridged carbon might be preferred). If so, on the account of the greater instability of ferrocenylcarbenium ions and the steric repulsion between the inner α-hydrogens of the ferrocenyl units, the iron at **226**, might be easily released to give the parent 1,12-dicyclopentadienylidene[1,1]-ferrocenophane (**218**).

* The ^1H and ^{13}C NMR spectra were complicated by the isomerism in the cyclopenadienide rings. This isomerism, arising from the position of the double bonds in the rings relative to the CH_2 bridge, only has an effect on the chemical shifts of reasonably close nuclei (this effect is only noticeable in some signals of the ^{13}C NMR spectrum). The NMR evidence indicated that approximately half of the terminal cyclopentadienes have the structure **223** and half have the structure **224** (thermodynamically more stable), with no evidence for the presence of any with structure **235**.



223 **224** **225**

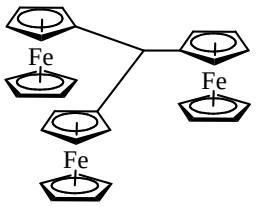


Computational chemistry may be able to model the trinuclear ferrocenophane system **34** well enough to give us answers to all these questions.

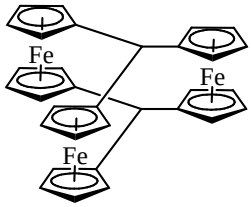
4 Summary and Outlook

The triphenylmethyl radical (**1**) is known not to dimerise to hexaphenylethane but to a quinoid dimer **5** with loss of the aromaticity of one benzene ring.[1, 4] As the aromaticity is more pronounced in ferrocene (**14**),[20] a similar behaviour would not be expected for the triferrocenylmethyl system **33**.[41] In addition, due to the three dimensional character of ferrocene (**14**), the triferrocenylmethyl system offers the possibility of a coupling of the additional cyclopentadienyl ligands. From compounds derived from **33** or **34** we expect highly interesting structural and electronic properties. Their synthesis and the study of their three dimensional architecture is the prime target of this project.

This work features our studies on the synthesis and the chemistry of the ferrocene analogues of triphenylmethane, **33** and **34**.



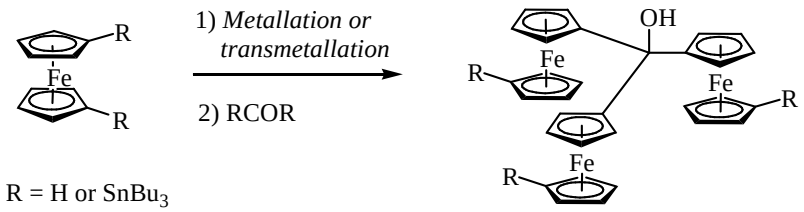
33[41]



34

The presence of more than one metal center within the same molecule profoundly affects both physical properties and the reactivity of the molecule. Although a wide range of molecular structures containing more than one ferrocene unit have been described, compounds in which three ferrocenes are linked together by one bridging methylene group have been investigated little so far and this is most likely because of the difficulties encountered in their synthesis.

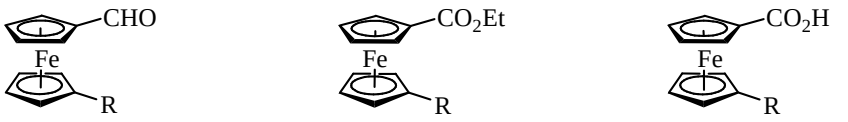
Threefold addition of a monolithiated ferrocene species [from direct monometallation of ferrocene (**14**) or from transmetallation of 1,1'-bis(tributylstannyl)ferrocene (**168**)] to an appropiate carbonyl compound leads to the parent carbinols **41** and **171**.



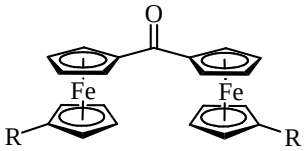
R = H or $SnBu_3$

41[41] R = H (63 %)
171 R = $SnBu_3$ (75%)

The synthetic usefulness of this method was demonstrated by the preparation of a wide range of some known as well as some new ferrocenecarboxylic derivatives **40**, **42**, **43**, **169** and **170**.

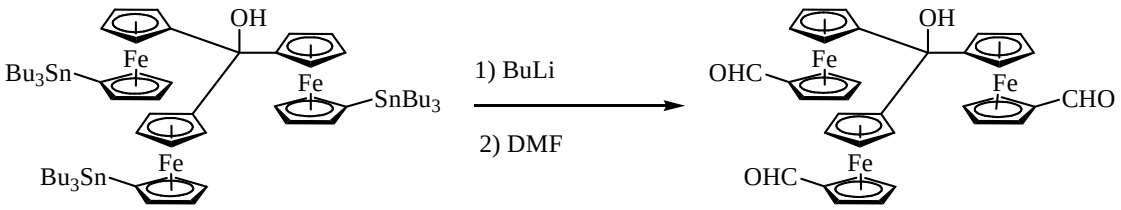


42[32] R = H (61%) **169** R = $SnBu_3$ (79%) **43**[33] R = H (54 %)



40[28] R = H (38 %)
170 R = $SnBu_3$ (55 %)

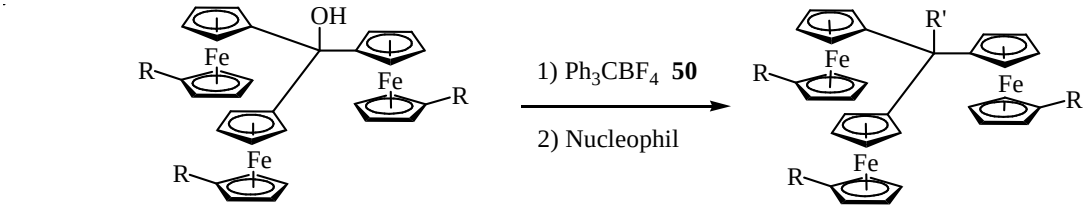
Modification of the substituents at the cyclopentadienyl ligands opposite to the coupling ones was possible taking advantage of the ability of stannyl substituents to be easily replaced by lithium.[97-99] In a brief assessment of the chemical properties of **171** and as a first test for the feasibility of a multiple transmetallation, **171** was formylated to the trisaldehyde **174**.



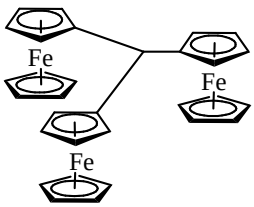
171

174 (26 %)
(64 % per formylation step)

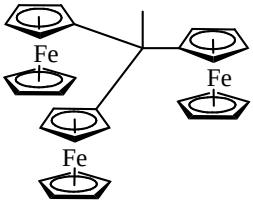
Alcohol abstraction of the parent carbinols **41** or **171** with triphenylmethylcarbenium tetrafluoroborate (**50**) and addition of a number of nucleophiles leads to some known as well as some unknown bridged substituted derivatives **33**, **51**, *rac*-**52**, **53**, **54**, **58**, **59, 175** and **228**.



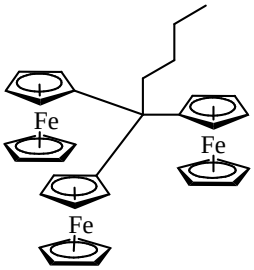
41 R = H
171 R = $SnBu_3$



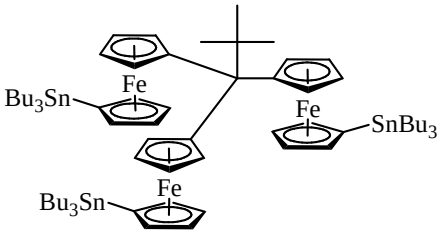
33[41] (36 %)



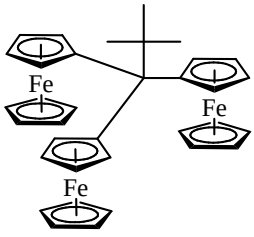
51[42] (28 %)



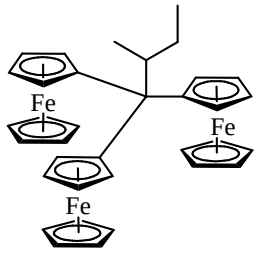
53[42] (63 %



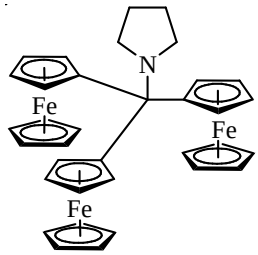
175 (36 %)



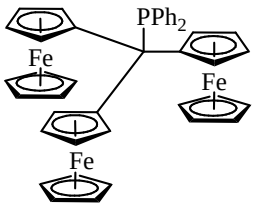
54[42] (16 %)



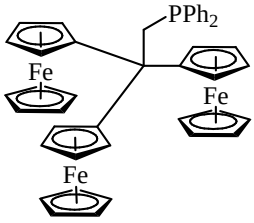
rac-**52** (50 %)



228 (91%)



59 (25 %)



58 (70 %)

Due to its three-dimensional extension ferrocene (**14**) often leads to strained or twisted molecules. Crystal structure analyses of triferrocenylmethane (**33**) and of 1,1,1-triferrocenyl-2,2-dimethylpropane (**54**) reveal that the conformation adopted by the triferrocenylmethyl group differs significantly with the steric bulk of the substituent at the central carbon atom.

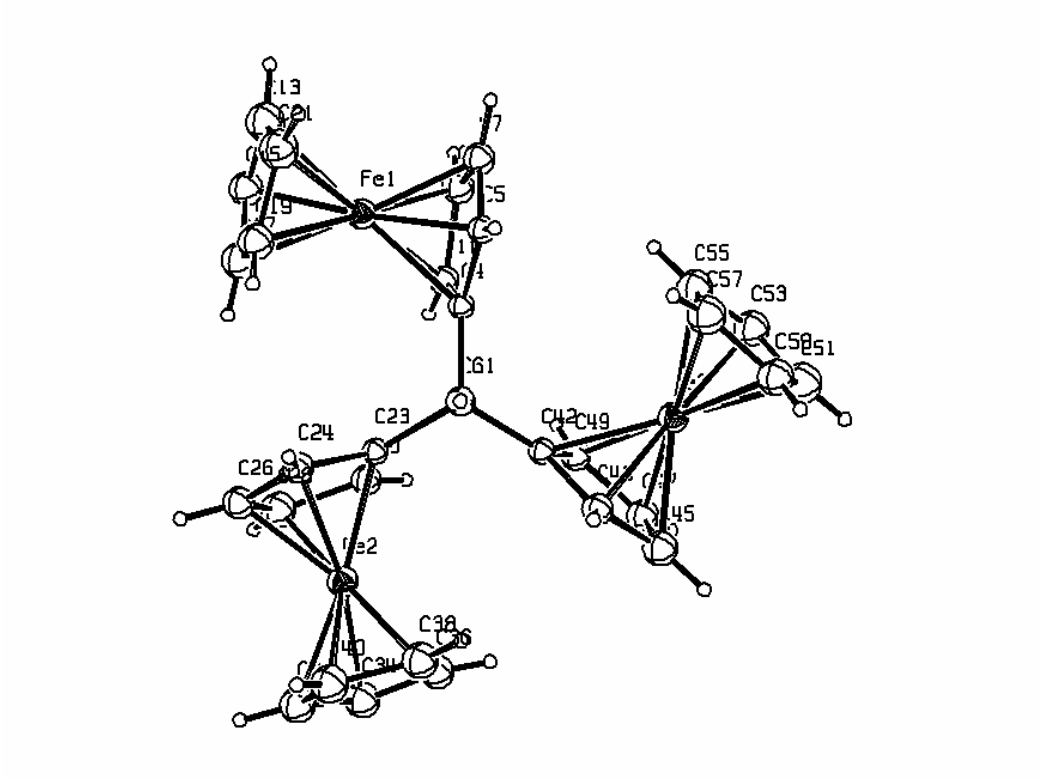


Fig. 25: ORTEP plot of the structure of **33** in the crystal.

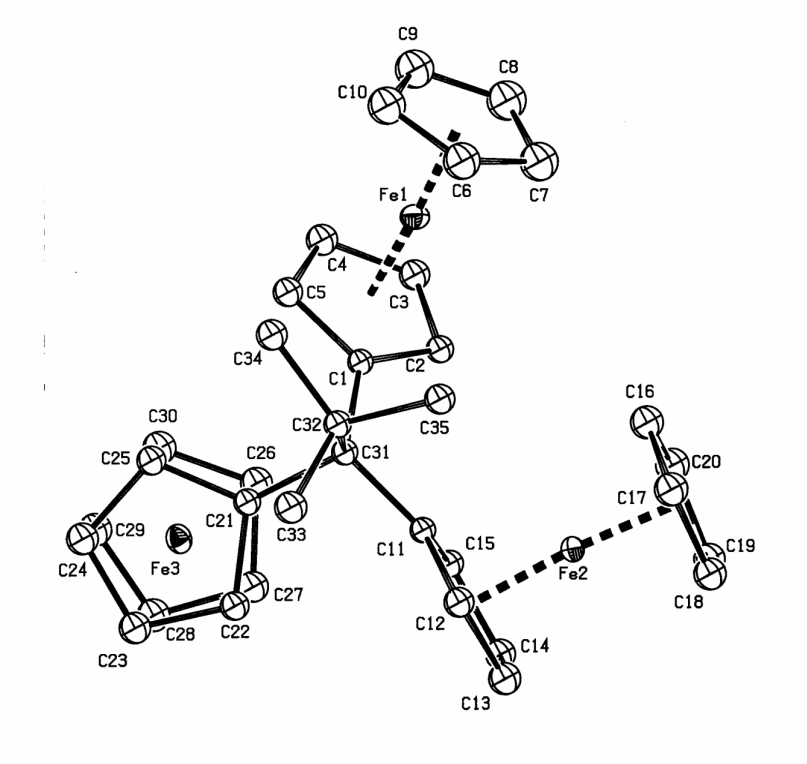
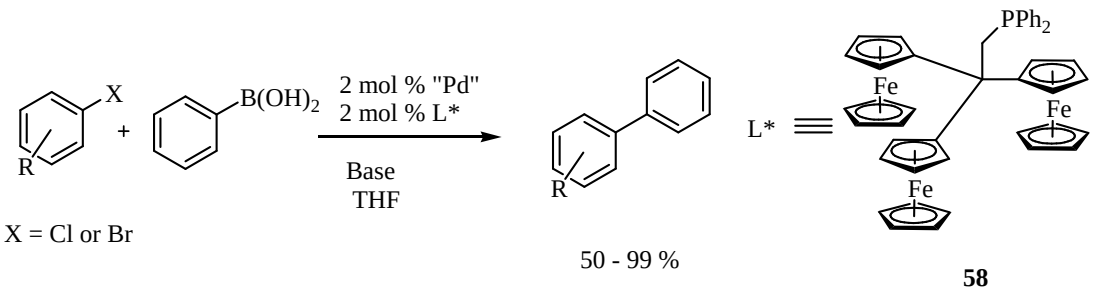


Fig. 26: ORTEP plot of the structure of **54** in the crystal.

The study of using bulky, electron-rich monodentate phosphine ligands for transition metal-catalyzed reactions has recently attracted much attention since they have been demonstrated as unique, highly efficient ligands for a number of transition metal catalyzed transformations. Due to the special spacial features of the triferrocenylmethane scaffold, the application of **58** in palladium cross-coupling reactions was tested [Pd(0)-catalyzed Suzuki-Miyaura cross-coupling reaction of aryl halides with phenylboronic acid].



X = Cl or Br

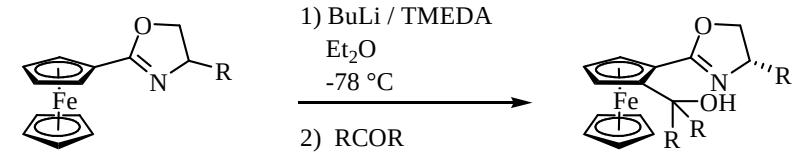
50 - 99 %

58

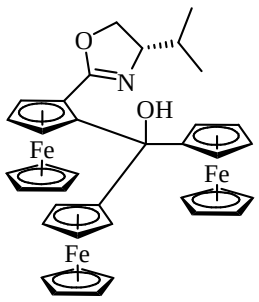
Chiral non-racemic ferrocene derivatives have attracted tremendous interest during recent years.[12] Among them, those that exhibit planar chirality are specially important because of their usefulness in asymmetric catalysis and material science.

As an extension of our work in the triferrocenylmethane field, we have developed two new general strategies for the asymmetric synthesis of planar chiral triferrocenylmethane derivatives.

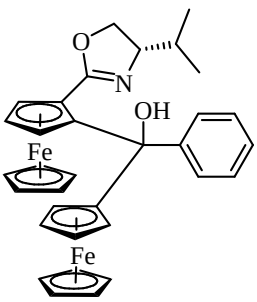
Ortho-lithiation of optically pure ferrocenyloxazolines (*S*)-**78** and (*S*)-**92**, followed by addition of a carbonyl substrate [benzophenone, ferrocenylphenylketone or diferrocenylketone (**40**)], leads to the diastereomerically enriched (> 95 % *dr* after column chromatography) 1,2-disubstituted ferrocenes (*S,Rp*)-**124**, (*S,Rp*)-**128**, (*S,Rp*)-**129** and **130**.



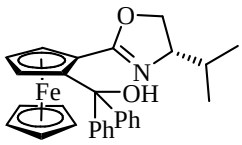
(*S*)-**78** R = *iso*Bu
(*S*)-**92** R = CMe_2OMe



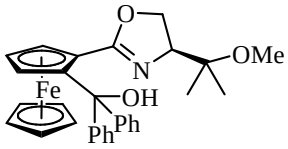
(*S,Rp*)-**129** (61%)



130 (80 %)
3:1 mixture of diastereoisomers



(*S,Rp*)-**128** (96 %)



(*S,Rp*)-**124** (63 %)

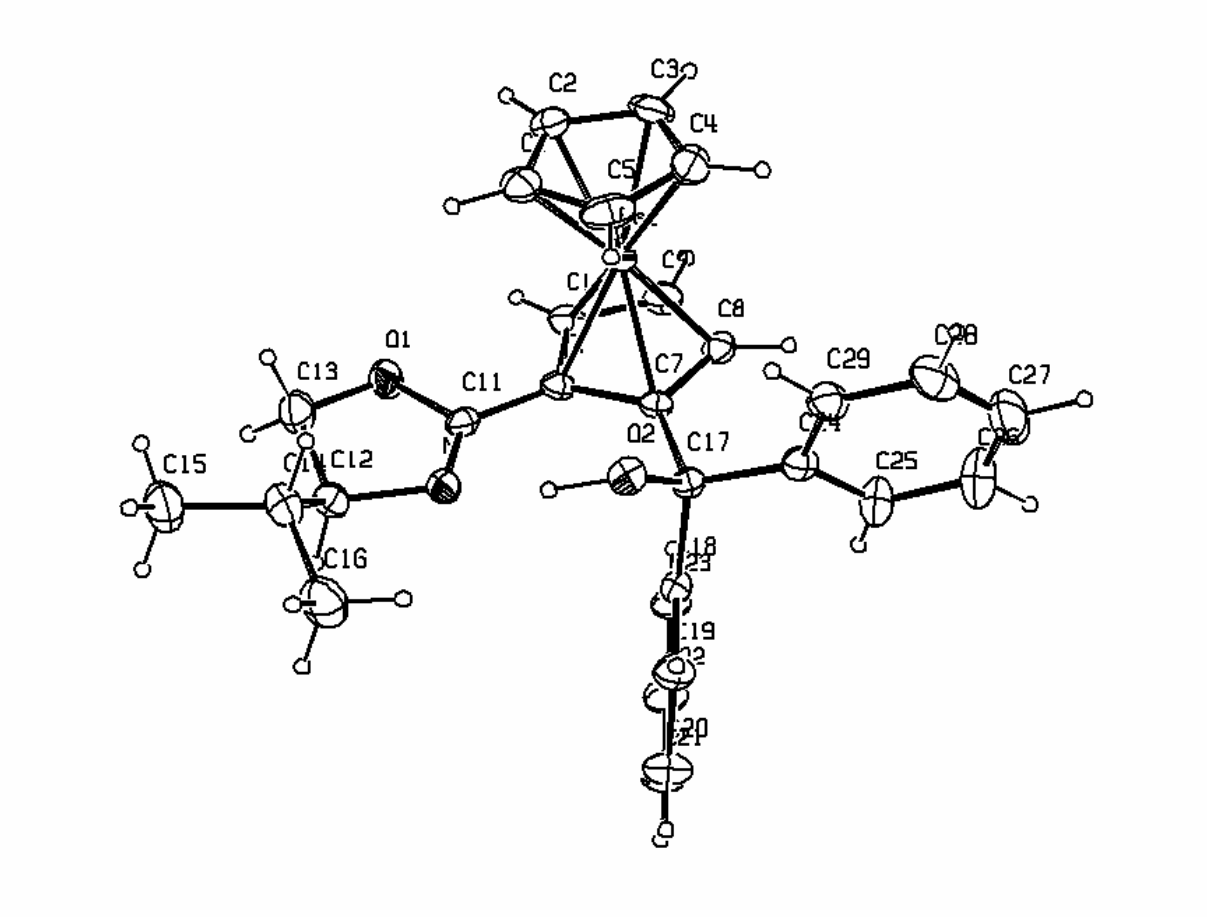
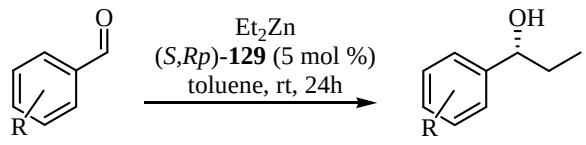


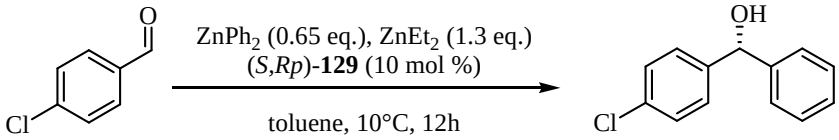
Fig. 27: ORTEP plot of the structure of (*S,Rp*)-**128** in the crystal.

Chiral non-racemic oxazolines have found widespread application as ligands in a multitude of metal catalyzed asymmetric reactions.[27] Among these ligands the substituted ferrocenyl-oxazolines constitute a special group as they posses both central and planar chirality. This type of chiral ligands have been extensively and successfully applied in palladium catalyzed allylic substitutions and in asymmetric additions of Zn(II)-reagents (alkylzincs, arylzincs, alkynylzincs) to aldehydes.[60]

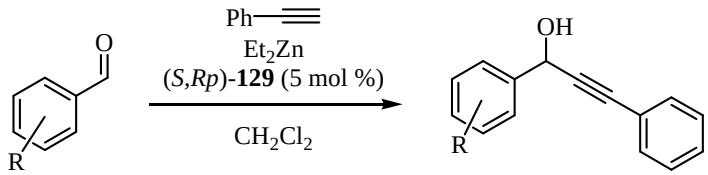
The usefulness of the new hydroxymethylferrocenyloxazoline (*S,Rp*)-**129** in asymmetric catalysis has been studied in the asymmetric addition of diethylzinc, phenylzinc and alkynylzinc to aldehydes.



80 - 99 % (80 - 97 % ee)



67 % (7 % ee)

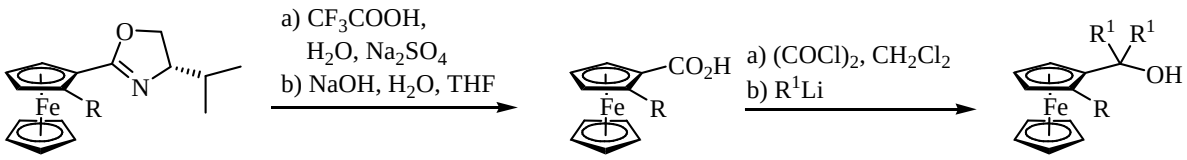


40 - 92 % (1 - 19 % ee)

The ability of the hydroxymethylferrocenyloxazoline scaffold to hold substituents in a well defined spatial proximity suitable for metal coordination, along with the presence of three bulky ferrocenyl groups which helps to create a sterically demanding environment around the central zinc atom, improves the stereochemical outcome in the diethylzinc addition. However, in the catalyzed addition of arylzinc or alkynylzinc to aldehydes, the large ferrocenyl units seem to interact with the bulky zinc reagents hampering somehow the normal approach of the substrate (or at least altering it), thereby leading to no good stereodifferentiation.

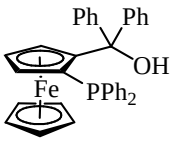
The above discussed methodology for the synthesis of chiral triferrocenylmethane derivatives [*ortho*-lithiation of ferrocenyloxazolines followed by quenching with diferrocenylketone (**40**)], has a clear disadvantage in that it is suitable only for the synthesis of oxazoline derivatives. In order to overcome this limitation a novel route was sought.

Ferrocenoyl chlorides generated *in situ* from α-substituted ferrocenecarboxylic acids (*Rp*)-**161** and (*Sp*)-**162** [from the ring opening of the parent substituted ferrocenyloxazolines (*e.g.* (*S,Rp*)-**159** or (*S,Sp*)-**160**], were treated with an excess of phenyllithium or monometallated ferrocene to give the enantiomerically pure carbinols **163 - 165**.

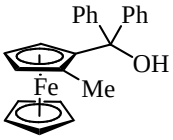


(*S,Rp*)-**159**[53 - 55] R = Me
(*S,Sp*)-**160**[53 - 55] R = PPh_2

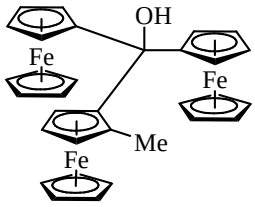
(*Rp*)-**161**[94] R = Me (49 %)
(*Sp*)-**162**[93] R = PPh_2 (72 %)



(*Sp*)-**163** (50 %)



(*Rp*)-**164** (35 %)



(*Rp*)-**165** (31 %)

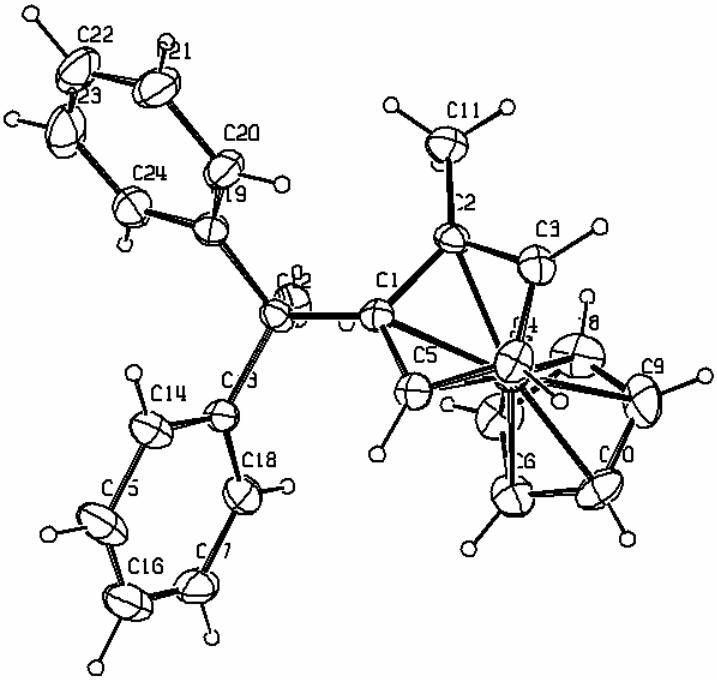
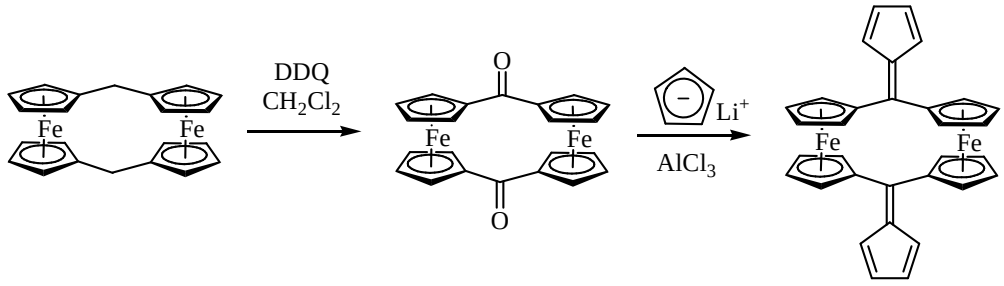


Fig. 28: ORTEP plot of the structure of (*Rp*)-**164** in the crystal.

Metallocenophanes are ring sytems in which the metallocene units are joined by an atomic or a molecular bridge. The compound [1,1]-ferrocenophane (**184**) in which two ferrocenes are linked together by two bridging methylene groups, is a very useful starting material for the synthesis of more complex metallocenophanes.

DDQ mediated oxidation to dione **191**, followed by treatment with lithium cyclopentadienide in the presence of $AlCl_3$ leads to difulvene **218**, advanced precursor of the desired compound **34**.



184[108] **191**[110] (76 %) **218** (98 %)

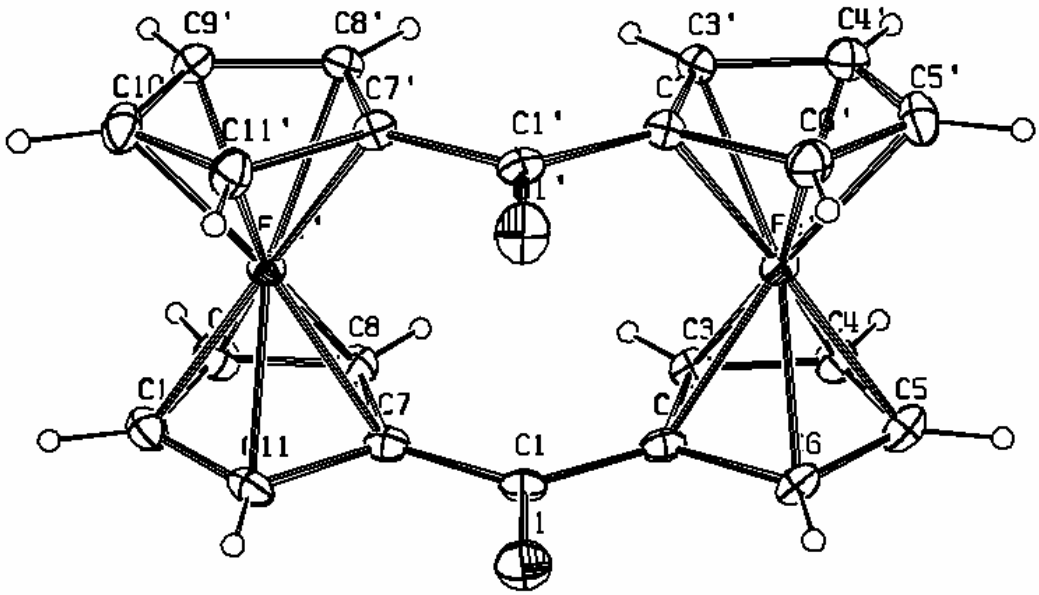
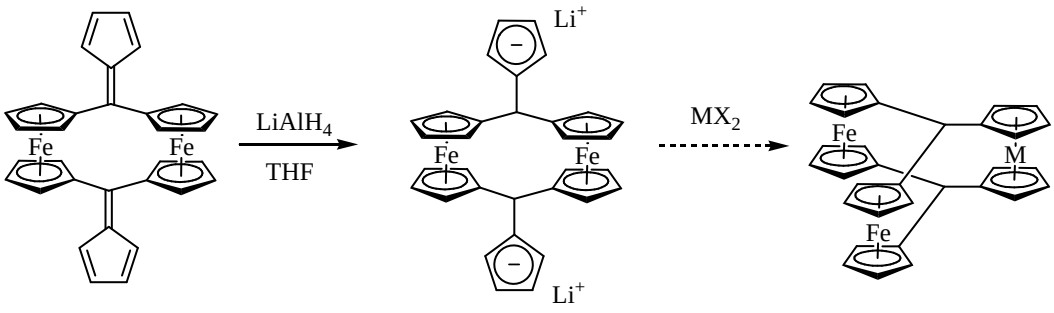


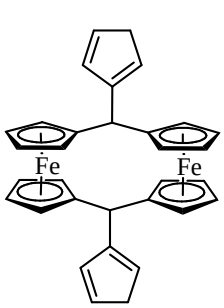
Fig. 29: ORTEP plot of the structure of **191** in the crystal.

Reduction of the difulvene **218** to the dianion **219** and metallation with $FeCl_2$.2THF should lead to the desired molecule **34**.

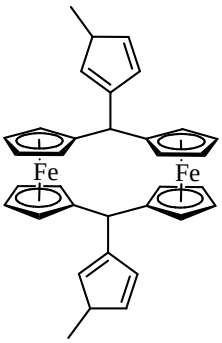


218 **219** (> 99 %) **34** M = Fe

Although isolation of compounds **221** and **220** (from the addition of H_2O or MeI to **219**) demonstrated the existence of the intermediate **219** in the foreseen sequence, the desired triferrocenylmethane derivative **34** has not been isolated until now.



221 (90 %)



220

5 Experimental Part

5.1 General Methods and Chemicals

All operations involving air- or moisture-sensitive compounds were carried out in an argon or nitrogen atmosphere, using standard Schlenk and vacuum line techniques. Glassware was heated at reduced pressure with a heat gun and flushed with argon or nitrogen. This procedure was repeated three times. Addition of all reagents as well as solvents was carried out with syringes equipped with steel needles in an argon or nitrogen steam. Labile chemicals were kept in a glove-box or refrigerator and stored under argon or nitrogen.

The following solvents were distilled before use under a slight positive pressure of nitrogen or argon, according to standard procedures. Diethyl ether (DEE), toluene, and tetrahydrofuran (THF) were distilled from sodium benzophenone ketyl. Methylene chloride, hexanes, *N*,*N*-diisopropylethylamine (Hünig´s Base), *N*,*N*,*N'*,*N'*-tetramethylethane-1,2-diamine (TMEDA) and triethylamine were distilled from calcium hydride. Petroleum ether (PE) and *tert*-butylmethyl ether (TBME) were distilled from calcium chloride. All the solvents, chloroform, methanol, ethanol, ethyl acetate (EE), were argonated before use.

Unless otherwise specified, all reagents were purchased from commercial suppliers (Across, Aldrich, Fisher-Scientific, Fluka, Lancaster, Merck, Sterm) and used without further purification [benzaldehyde, 3-phenylpropenal, Lawesson´s reagent, 4-chlorobenzaldehyde, 4-methoxybenzaldehyde, *t*-butyllithium 1.7 M in pentane, aluminum chloride, chlorodiphenylphosphine, L-valinol (**80**), L-serine (**82**), carbamoyl chloride, methyllithium 1.6 M in cyclohexane, buthyllithium 1.6 M in hexane, *s*-buthyllithium (*s*-BuLi) 1.6 M in hexane, triphenylmethylcarbenium tetrafluoroborate (**50**), ferrocene (**14**), ethyl chloroformate, diethylaminosulfur trifluoride (DAST), methylmagnesiumiodide 3 M in DEE, phenyllithium 1.8 M in cyclohexane, 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ), trimethylsilylchloride (Me_3SiCl), pyrrolidine]. All the amino acids employed in practice were received from Degussa AG. KF was dried in an oven overnight prior to use.

Preparative column chromatography was performed by flash chromatography[126] on silica gel (J. T. Barker, ∅ 40 μm), neutral aluminum oxide (Al_2O_3, Fluka, Brockmann activity I, ∅ 0.05 - 0.15 mm, pH 7.0 ± 0.5), and basic aluminum oxide (Al_2O_3, ∅ 0.05 - 0.15 mm,

Brockmann activity II,III or IV). When necessary, silica gel was degassed by heating it with a heat gun at reduced pressure followed by setting it at normal pressure with argon or nitrogen. This procedure was repeated three times.

Thin-layer chromatography (TLC) analysis was performed using aluminum TLC plate coated with the silica gel $60F_{254}$ from Merck combined with the polygram®. Visualization was effected by ultraviolet light (254 nm) or by developing with ceriumammoniumnitrate reagent.

^{1}H NMR, ^{13}C NMR and ^{31}P NMR spectra were recorded at 25 °C on a Bruker AM 400 (^{1}H: 400.1 MHz, ^{13}C: 100.1 MHz, ^{31}P: 161.9 MHz) or WP 200 SY (^{1}H: 200.1 MHz, ^{13}C: 50.3 MHz) spectrometer. The chemical shifts are given in ppm using tetramethylsilane (δ = 0.00 ppm) or residual solvent signals (acetone δ = 2.09 ppm, chloroform δ = 7.26) as internal standards. In ^{31}P NMR a solution of H_3PO_4 85 % in water is used as external reference. The following abbreviations are for the signals multiplicities observed: s (singlet), d (doublet), t (triplet), q (quartet), m (multiplet), br (broad). In ^{13}C NMR, signal multiplicities were determined by APT or DEPT techniques and peaks with negative phase for CH and CH_3 are labeled with " – ", and those with positive phase for C and CH_2 are labeled with " + ". Air sensitive samples were prepared under argon using standard Schlenk techniques, and the deuterated solvents were stored under argon.

Infrared spectra (IR) were recorded on a Perkin-Elmer FT-IR 580 and 1710 spectrometers. The following abbreviations are for the signals intensities observed: s (strong), m (medium), w (small), br (broad).

Mass spectra (MS) were recorded on a Micromass LCT with Lock-Spray-unit (ESI). The injection was made in Loop-Modus in a HPLC-Alliance 2695 (Waters). All values are given in atomic units of mass per elemental charge (m / z). The intensity is given as a percentage of the base peak.

High resolution mass spectra (**HRMS)** were recorded with the Peak-Matching method in a Micromass LCT with Lock-Spray-unit (ESI). All values are given in atomic units of mass per elemental charge (m / z).

Optical rotations Optical rotations were determined on a Perkin Elmer PE-241 instrument at 25 °C. The measurements were carried out using a light frequency of 589 nm (D-line of a sodium vapour lamp) in a cuvette [length d = 1 dm or d = 0.1 dm; concentration (c) is given in g / 100 ml].

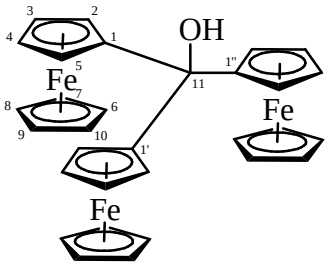
Melting points (*m.p.*) were determined with a Büchi apparatus according to Dr. Tottoli and are uncorrected.

Elemental analyses (EA) Microanalyses were conducted on an Elementar Vario EL with acetanilide as standard. All values are given as mass percentages.

Microwave Oven (µW) Microwave heating was carried out with a Discover® LabMate™ single-mode microwave cavity operating at 250 W from CEM Corporation. The reactions were conducted in a 10 mL sealed Pyrex vessel, with a maximum operating temperature of 150 °C and a maximum operating pressure of 8 bar.

5.2 Triferrocenylmethane Derivatives

5.2.1 Triferrocenylmethanol (41)[28, 40, 123]

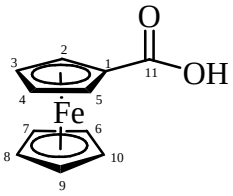


$C_{31}H_{28}Fe_3O$
Mol. Wt.: 584.1

41

Ferrocene (**14**) (2.000 g, 10.7 mmol) in 5 mL of anhydrous hexane and 5 mL of anhydrous THF was stirred for 30 min at 25 °C and then cooled to 0 °C. *t*-BuLi (6.00 mL, 1.7 M in pentane, 10.2 mmol) was slowly added over 10 min, and the mixture was stirred for 1h at 0 °C. At this point, freshly distilled ethyl chloroformate (0.15 mL, 1.6 mmol) was added and the colour of the mixture changed from yellow to black. The reaction was allowed to warm to 25 °C, and after 1 h at 25 °C, hydrolysis was performed by addition of 20 mL of MeOH. The organic layer was diluted with 50 mL of CH_2Cl_2, washed with 3 x 20 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2 deactivated with Et_3N 5% in PE, 25 x 4 cm, PE / $CHCl_3$ 3:1) gave pure triferrocenylmethanol (**41**) (0.590 g, 1.0 mmol, 63 %), identified by comparison with an authentic sample (^1H NMR).[40, 123]

5.2.2 Ferrocenecarboxylic acid (43)[127]

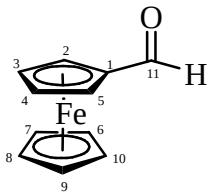


$C_{11}H_{10}FeO_2$
Exact Mass: 230.0

43

Ferrocene (**14**) (0.250 g, 1.3 mmol) in 0.62 mL of anhydrous hexane and 0.62 mL of anhydrous THF was stirred for 30 min at 25 °C and then cooled to 0 °C. *t*-BuLi (0.75 mL, 1.7 M in pentane, 1.3 mmol) was slowly added over 10 min, and the mixture was stirred for 1h at 0 °C. At this point, the reaction mixture was added to solid CO_2. Hydrolysis was performed by addition of 20 mL of a 2N aqueous solution of NaOH. The aqueous phase was washed 3 x 25 mL of PE, acidified until pH = 4 with concentrated HCl and extracted with 2 x 25 mL of CH_2Cl_2. The organic layer was washed with 3 x 20 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure to give pure ferrocenecarboxylic acid (**43**) (0.157 g, 0.7 mmol, 54 %), identified by comparison with an authentic sample (^{1}H NMR).[127]

5.2.3 Ferrocenecarboxylic aldehyde (42)[128]



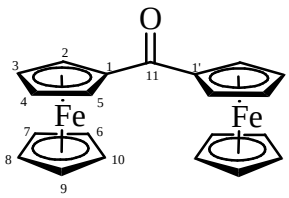
$C_{11}H_{10}FeO$
Exact Mass: 214.0

42

Ferrocene (**14**) (0.250 g, 1.3 mmol) in 0.62 mL of anhydrous hexane and 0.62 mL of anhydrous THF was stirred for 30 min at 25 °C and then cooled to 0 °C. *t*-BuLi (0.75 mL, 1.7 M in pentane, 1.3 mmol) was slowly added over 10 min, and the mixture was stirred for 1h at 0 °C. At this point, freshly distilled DMF (0.20 mL, 2.5 mmol) was added dropwise. The reaction mixture was allowed to warm to 25 °C, and after 1 h at 25°C, hydrolysis was

performed by addition of 100 mL of H_2O. The organic layer was diluted with 100 mL of CH_2Cl_2, washed with 3 x 20 mL of a 3 M aqueous solution of HCl, 3 x 20 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2 deactivated with Et_3N 5% in PE, 25 x 4 cm, CH_2Cl_2) gave pure ferrocenecarboxylic aldehyde (**42**) (0.163 g, 0.8 mmol, 61 %), identified by comparison with an authentic sample (^{1}H NMR).[128]

5.2.4 Diferrocenylketone (40)[127, 129]

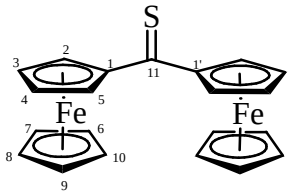


$C_{21}H_{18}Fe_2O$
Exact Mass: 398.0

40

Ferrocene (**14**) (5.000 g, 26.8 mmol) in 12.5 mL of anhydrous hexane and 12.5 mL of anhydrous THF was stirred for 30 min at 25 °C and then cooled to 0 °C. *t*-BuLi (15.00 mL, 1.7 M in pentane, 25.5 mmol) was slowly added over 10 min, and the mixture was stirred for 1 h at 0 °C. At this point, freshly distilled carbamoyl chloride (1.2 mL, 13.0 mmol) in 10 mL of anhydrous THF was slowly added over 30 min. The reaction mixture was allowed to warm to 25 °C, and after 1 h at this temperature, hydrolysis was performed by addition of 100 mL of H_2O. The organic layer was diluted with 100 mL of CH_2Cl_2, washed with 3 x 20 mL of a 3 M aqueous solution of HCl, 3 x 20 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2, 25 x 4 cm, PE / CH_2Cl_2 3:1) gave pure diferrocenylketone (**40**) (1.940 g, 4.9 mmol, 38 %), identified by comparison with an authentic sample (^{1}H NMR).[129]

5.2.5 Diferrocenylthioketone (200)[120]

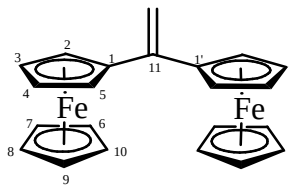


$C_{21}H_{18}Fe_2S$
Exact Mass: 414.0

200

A solution of diferrocenylketone (**40**) (0.150 g, 0.4 mmol) and Lawesson´s reagent (0.120 g, 0.2 mmol) in 30 mL of anhydrous toluene was heated at reflux for 3 h under nitrogen. This solution was filtered through SiO_2 (25 x 4 cm, CH_2Cl_2) to give pure diferrocenylthioketone (**200**) (0.084 g, 0.2 mmol, 54 %), identified by comparison with an authentic sample (^{1}H NMR).[120]

5.2.6 1,1-Diferrocenylethene (201)[122]



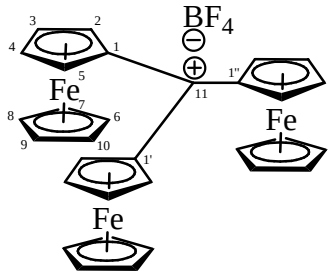
$C_{22}H_{20}Fe_2$
Exact Mass: 396.0

201

At 25 °C, a suspension of diferrocenylketone (**40**) (0.236 g, 0.6 mmol) and $AlCl_3$ (0.130 g, 1.0 mmol) in 20 mL of anhydrous THF was treated with MeLi (1.54 ml, 1.6 M in cyclohexane, 2.5 mmol). After 1 h, hydrolysis was performed by addition of 10 mL of H_2O. The reaction mixture was diluted with 50 ml of CH_2Cl_2 and the organic layer was washed with 3 x 25 mL of H_2O, dried over $MgSO_4$, and the resulting solution was mixed with neutral aluminum oxide (1 g). The solvent was removed at reduced pressure and column chromatography (neutral aluminum oxide, 25 x 2 cm, CH_2Cl_2) gave pure 1,1-diferrocenylethene (**201**) (0.222 g, 0.6 mmol, 95 %), identified by comparison with an authentic sample (^{1}H NMR).[122]

5.3 Synthesis of Bridged Substituted Triferrocenylmethane Derivatives

5.3.1 Triferrocenylmethyl tetrafluoroborate (48)



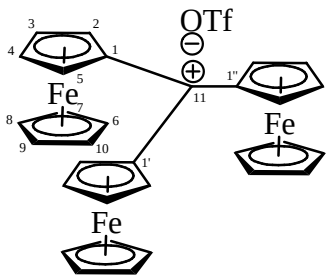
$C_{31}H_{27}BF_4Fe_3$
Mol. Wt.: 653.9

48

At 25 °C, a well stirred suspension of triferrocenylmethanol (**41**) (0.537 g, 0.9 mmol) in 20 mL of anhydrous THF, was treated with Ph_3CBF_4 (0.370 g, 1.1 mmol) and the colour of the mixture changed immediately from yellow to blue-black. The reaction mixture was stirred at 25 °C for 2 h until no starting material remained (TLC, CH_2Cl_2). Then the solvent was removed at reduced pressure, and the remaining dark solid was washed with 3 x 20 mL of anhydrous hexane to give pure triferrocenylmethyl tetrafluoroborate (**48**) as a green-blue solid (0.524 g, 0.8 mmol, 87 %), which does not melt till 250 °C.

48: IR (ATR): $\tilde{\nu}$ = 3100 cm^{-1} (w, Cp-H), 1439 (s), 1023(s), 1002 (s), 853 (s). - ^{1}H NMR (400 MHz, [D_6]-acetone): δ = 4.69 (s, 15H, CpH), 5.68 + 5.70 (AA'BB' line system, 2 x 6H, CpR) ppm. - ^{13}C NMR (100 MHz, BB, [D_6]-acetone): δ = 75.4 (*C*H-CpH), 80.6 (*C*H-CpR), 81.8 (*C*H-CpR), 89.3 (*C*R-CpR) 209.0 (C-11) ppm. - MS (ESI, ES^+): *m / z* = 567 [M^+]. - $C_{31}H_{27}BF_4Fe_3$: calcd. C 56.94, H 4.16; found C 56.98, H 4.16.

5.3.2 Triferrocenylmethyl triflate (49)



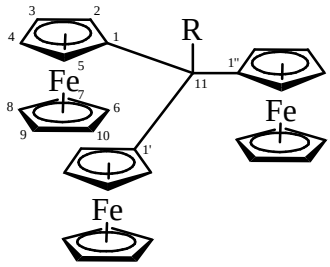
$C_{32}H_{27}F_3Fe_3O_3S$
Mol. Wt.: 716.1

49

At 25 °C, a well stirred suspension of triferrocenylmethanol (**41**) (0.250 g, 0.4 mmol) in 20 mL of anhydrous DEE, was treated with $(CF_3SO_2)_2O$ (0.35 mL, 2.0 mmol) and the solution immediately turned blue-black. The reaction mixture was stirred at 25 °C for 2 h until no starting material remained (TLC, CH_2Cl_2), and then the solvent was removed at reduced pressure. The dark solid was washed with 3 x 20 mL anhydrous DEE to give pure triferrocenylmethyl triflate (**49**) as a green-blue solid (0.293 g, 0.4 mmol, 96 %).

49: MS (ESI, ES^+): *m / z* = 567 [M^+]. - HRMS (ESI) ($C_{31}H_{27}Fe_3$): calcd. 567.0161; found: 567.0139 [M]. - MS (ESI, ES^-): *m / z* = 148 [OTf^-]. - HRMS (ESI) (CO_3F_3S): calcd. 148.9520; found 148.9525 [OTf].

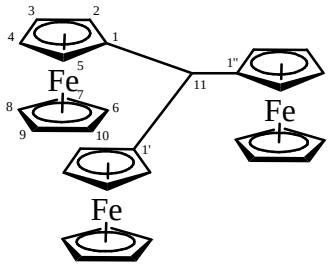
5.3.3 General Procedure for Reactions of 48 with Nucleophiles (GP1)



At –78 °C, a well stirred solution of the nucleophil in anhydrous THF was treated with triferrocenylmethyl tetrafluoroborate (**48**). The solution was allowed to warm to 25 °C, and after 20 min at 25 °C, hydrolysis was performed by addition of H_2O. The crude reaction

mixture was diluted with TBME, and the organic layer was washed three times with water each and dried over $MgSO_4$. The solvent was removed at reduced pressure, giving the pure product after recrystallization or column chromatography.

5.3.4 Triferrocenylmethane (33)[41]



$C_{31}H_{28}Fe_3$
Mol. Wt.: 568.1

33

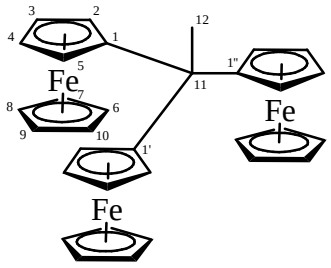
GP1: **48** (0.500 g, 0.8 mmol); $LiAlH_4$ (0.870 g, 23.0 mmol); DEE (150 mL); recrystallization from PE gave triferrocenylmethane (**33**) (0.156 g, 0.3 mmol, 36 %) as a yellow solid, (*m.p.* > 200 °C, *dec*.), identified by comparison with an authentic sample (^{1}H NMR).[41, 42]

33: IR (ATR): $\tilde{\nu}$ = 3092 cm^{-1} (m, Cp-H), 1454 (m), 1409 (m, CH), 1104 (s), 1036 (s), 1000 (s), 817 (s), 807 (s, Cp-H). - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 3.97 (s, 15H, CpH), 4.10 (AA'BB' line system, 2 x 6H, CpR), 4.16 (s, 1H, 11-H) ppm. - ^{13}C NMR (100 MHz, BB, HMQC, HMBC, $CDCl_3$): δ = 38.7 (C-11), 66.5 (*C*H-CpR), 68.4 (*C*H-CpR), 68.9 (*C*H-CpH), 95.7 (*C*R-CpR) ppm.

Crystal Structure Analysis of **33:** $C_{31}H_{28}Fe_3$, molecular weight, 568.08 g / mol, temperature 300 K, crystal system orthorhombic, space group Pbca, a = 9.394(2), b = 18.354(4), c = 27.517(7) Å, α = 90°, β = 90°, γ = 90°, V = 4744(2) Å^3, Z = 8, $\rho_{calcd.}$ = 1.591 g cm^{-3}, F(000) = 2336, Absorption coefficient = 1.829 mm^{-1}, crystal size 0.48 x 0.22 x 0.20 mm, Stoe IPDS area detector diffractometer, θ-range = 2.34 to 24.19°, limiting indices –10<=h<=10, –20<=k<=20, –31<=l<=31, reflections collected / unique 37426 / 3545 [R(int) = 0.2405], 1229 observed (I>2σ(I)) [R_{int} = 0.074], completeness of data: 93.8%, no absorption correction, no

extinction correction, refinement method Full-matrix least-squares on F^2, goodness-of-fit on F^2 = 1.157, R_1 = 0.0776, wR_2 = 0.0993 [I>2 σ (I)], minimal and maximal residual electron density –0.5 / 0.6 eÅ^{-3}.

5.3.5 1,1,1-Triferrocenylethane (51)[42]



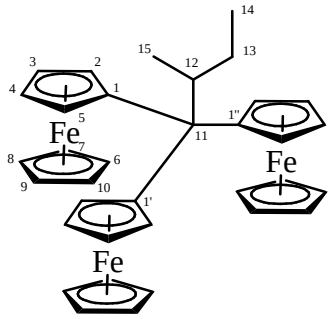
$C_{32}H_{30}Fe_3$
Mol. Wt.: 582.1

51

GP1: **48** (0.100 g, 0.2 mmol); MeLi (0.35 ml, 1.6 M in DEE, 0.6 mmol); THF (10 mL); recrystallization from PE gave 1,1,1-triferrocenylethane (**51**) (0.025 g, 0.04 mmol, 28 %) as a yellow solid (m. p. 308 - 310 °C), identified by comparison with an authentic sample (^{1}H NMR.[42]

51: IR (ATR): $\tilde{\nu}$ = 3079 cm^{-1} (m,Cp-H), 2962 (m, CH), 1258 (s), 1085 (s), 1003 (s, Cp-H), 791 (s, Cp-H). - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.10 (s, 3H, 12-H), 4.00 + 4.10 (AA'BB' line system, 2 x 6H, CpR), 4.04 (s, 15H, CpH) ppm. - ^{13}C NMR (100 MHz, BB, HMQC, HMBC, $CDCl_3$): δ = 26.8 (C-12), 36.6 (C-11), 66.4 (*C*H-CpR), 67.8 (*C*H-CpR), 68.7 (*C*H-CpH), 102.2 (*C*R-CpR) ppm.

5.3.6 *rac*-1,1,1-Triferrocenyl-2-methylbutane (52)



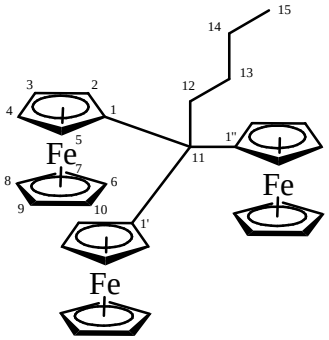
$C_{35}H_{36}Fe_3$
Mol. Wt.: 624.2

rac-**52**

GP1: **48** (0.114 g, 0.2 mmol); *s*-BuLi (0.90 ml, 1.6 M in hexane, 0.2 mmol); THF (10 mL); recrystallization from PE gave *rac*-1,1,1-triferrocenyl-2-methylbutane (**52**) (0.055 g, 0.1 mmol, 50 %) as a yellow solid (m. p. 177.5 - 178 °C).

***rac*-52:** IR (ATR): $\tilde{\nu}$ = 3095 cm^{-1} (w, Cp-H), 2955 (w), 2870 (w, CH), 1104 (s), 1052 (s), 997 (s, Cp-H), 805 (s, Cp-H). - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.63 (m, 1H, 12-H or 13-H), 0.96 (t, ^3J = 7.3 Hz, 3H, 14-H), 1.25 (d, ^3J = 6.6 Hz, 3H, 15-H), 2.08 (m, 1H, 12-H or 13-H), 2.9 (m, 1H, 12-H or 13-H), 4.05 (s, 15H, CpH), 4.17 (m, 3H, CpR), 4.20 (m, 3H, CpR), 4.40 (m, 3H, CpR), 4.50 (m, 3H, CpR) ppm. - ^{13}C NMR (100 MHz, BB, HMQC, HMBC, $CDCl_3$): δ = 13.4 (C-14), 16.2 (C-15), 26.8 (C-12 or C-13), 46.0 (C-12 or C-13), 46.3 (C-11), 66.0 (*C*H-CpR), 66.4 (*C*H-CpR), 69.2 (*C*H-CpR), 69.4 (*C*H-CpH), 69.8 (*C*H-CpR), 98.2 (*C*R-CpR) ppm. - MS (ESI, ES^+): *m / z* = 624 [M^+]. - HRMS (ESI) ($C_{35}H_{37}Fe_3$): calcd. 625.0943; found 625.0949 [M+H]. - $C_{35}H_{36}Fe_3$: calcd. C 67.35, H 5.81; found C 66.61, H 5.743.

5.3.7 1,1,1-Triferrocenylpentane (53)[42]



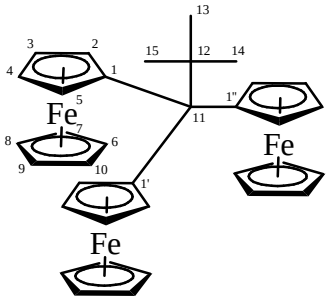
$C_{35}H_{36}Fe_3$
Mol. Wt.: 624.2

53

GP1: **48** (0.099 g, 0.2 mmol); BuLi (0.94 mL, 1.6 M in hexane, 1.5 mmol); THF (10 mL); recrystallization from PE gave 1,1,1-triferrocenylpentane (**53**) (0.059 g, 0.1 mmol, 63 %) as yellow crystals (m. p. 232 °C), identified by comparison with an authentic sample (^{1}H NMR).[42]

53: IR (ATR): $\tilde{\nu}$ = 3086 cm^{-1} (m, Cp-H), 2949 (m, CH), 2866 (m, CH), 1105 (s), 1028 (s), 1000 (s, =CH), 814 (s), 757 (s), 697 (s, Cp-H). - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.98 (t, ^3J = 7.3 Hz, 3H, 15-H), 1.34 - 1.40 (m, 2H, 14-H), 1.65 - 1.70 (m, 2H, 13-H), 2.32 - 2.33 (t, 2H, 12-H), 4.00 (s, 15H, CpH), 4.11 + 4.24 (AA'BB' line system, 2 x 6H, CpR) ppm. - ^{13}C NMR (100 MHz, BB, APT, HMQC, HMBC, $CDCl_3$): δ = 14.4 (–, C-15), 23.9 (+, C-14), 28.0 (+, C-13), 40.8 (+, C-11), 43.7 (+, C-12), 66.1 (–, *C*H-CpR), 68.0 (–, *C*H-CpR), 69.0 (–, *C*H-CpH), 99.3 (+, *C*R- CpR) ppm.

5.3.8 1,1,1-Triferrocenyl-2,2-dimethylpropane (54)[42]



$C_{35}H_{36}Fe_3$
Mol. Wt.: 624.2

54

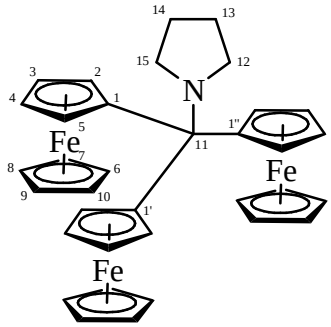
At 25 °C, a well stirred solution of triferrocenylmethanol (**41**) (0.587 g, 1.0 mmol) in anhydrous DEE (100 mL) was treated with Ph_3CBF_4 (0.366 g, 1.1 mmol) and the colour of the mixture changed immediately from yellow to blue-black. The reaction mixture was stirred under nitrogen at 25 °C for 2 h until no starting material remained (TLC, CH_2Cl_2). The green precipitate **48** was filtered, washed with 3 x 50 mL of anhydrous DEE to remove the formed triphenylmethanol (**9**), dissolved in 50 ml of anhydrous THF and cooled to –78 °C. *t*-BuLi (1.30 mL, 1.7 M in hexane, 2.2 mmol) was added to this solution. The reaction mixture was allowed to warm to 25 °C and after 1 h at 25 °C, hydrolysis was performed by addition of 25 mL of H_2O. The organic layer was washed with 3 x 20 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2, 24 x 4 cm, PE) gave 1,1,1-triferrocenyl-2,2-dimethylpropane (**54**) (0.232 g, 0.4 mmol, 37 %), as yellow crystals. Recrystallization from benzene (**15**) gave pure crystals (0.103 g, 0.2 mmol, 16 %) of **54** (*m. p.* 200 - 201 °C), suitable for an X-ray structure analysis.

54: IR (ATR): $\tilde{\nu}$ = 3091 cm^{-1} (m. Cp-H), 2901 (m, CH), 1477 (m), 1392 (m, CH_2), 1106 (s), 1052 (s), 1037 (s), 1000 (s, Cp-H), 814 (s, Cp-H), 684 (s), 660 (s). - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.30 [s, 9H, 13(14, 15)-H], 4.05 (s, 15H, CpH), 4.17 + 4.49 (AA'BB' line system, 2 x 6H, CpR) ppm. - ^{13}C NMR (100 MHz, BB, APT, HMQC, HMBC, $CDCl_3$): δ = 31.3 [–, C-13(14, 15)], 38.9 (+, C-12), 49.9 (+, C-11), 65.5 (–, *C*H-CpR), 69.6 (–, *C*H-CpH), 70.3 (–, *C*H-CpR), 98.6 (+, *C*R-CpR) ppm.

Crystal Structure Analysis of **54:** $C_{38}H_{39}Fe_3$ ($C_{35}H_{36}Fe_3$ • 0.5 C_6H_6), molecular weight, 663.24 g / mol, T = 300(2) K, red prism II a, crystal system triclinic, space group P^{-1}, (No. 2), *a* = 9.132(3), *b* = 11.416(4), *c* = 14.467(4) Å, α = 103.94(4)°, β = 90.80(4)°, γ = 93.14(4)°, *V*

= 1461.0(8) Å^3, Z = 2, $\rho_{calcld.}$ = 1.508 g/cm^3, F(000) = 690e, μ = 1.496 mm^{-1}, crystal size 0.67 x 0.25 x 0.06 mm, Stoe IPDS diffractometer, MoK$_\alpha$= 0.71073 A, $2\theta_{min}$ = 4.10°, $2\theta_{max}$ = 26.02°, –10<=h<=11, –14<=k<=14, –17<=l<=17, 17364 measured, 5332 unique [R_{int} = 0.0501], and 3426 observed reflections, completeness of data: 92.7%, no absorption correction, no extinction correction, 370 refined parameters, $R_{gt}(F)$ = 0.0350, $wR(F^2)$ = 0.0681, goodness-of-fit 1.042, minimal and maximal residual electron density –0.33 / 0.49 eÅ^{-3}.

5.3.9 *N*-(Triferrocenylmethyl)pyrrolidine (228)



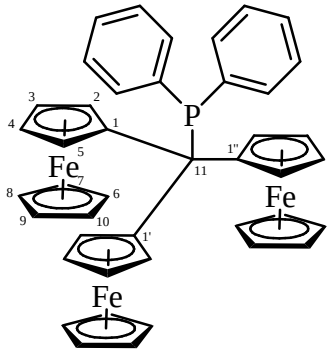
$C_{35}H_{35}Fe_3N$
Mol. Wt.: 637.2

228

GP1: **48** (0.111 g, 0.2 mmol); pyrrolidine (0.20 ml, 2.4 mmol); THF (10 mL); recrystallization from PE gave pure *N*-(triferrocenylmethyl)pyrrolidine (**228**) (0.099 g, 0.2 mmol, 91 %) as a yellow-red solid (m. p. 100 °C).

228: IR (ATR): $\tilde{\nu}$ = 3089 cm^{-1} (w, Cp-H), 2960 (w), 2924 (w), 2871 (w), 2811 (w, CH), 1104 (s), 1053 (s), 1031 (s), 1000 (s, Cp-H), 797 (s, Cp-H). - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.63 [s, 4H, 13(14)-H], 3.05 [s, 4H, 12(15)-H], 4.03 (s, 15H, CpH), 4.16 + 4.49 (AA'BB' line system, 2 x 6H, CpR) ppm. - ^{13}C NMR (100 MHz, BB, APT, HMQC, HMBC, $CDCl_3$): δ = 23.0 [+, C-13(14)], 47.8 [+, C-12(15)], 62.0 (+, C-11), 66.1 (–, *C*H-CpR), 69.4 (–, *C*H-CpH), 69.5 (–, *C*H-CpR), 94.9 (+, *C*R-CpR) ppm. - MS (ESI, ES$^+$): *m* / *z* = 567 [M$^+$–N(CH$_2$CH$_2$)$_2$].

5.3.10 Diphenyl(triferrocenylmethyl)phosphine (59)



$C_{43}H_{37}Fe_3P$
Mol. Wt.: 752.3

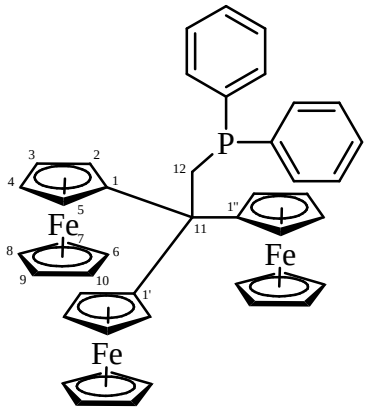
59

GP1: **48** (2.5 g, 3.8 mmol); lithiodiphenylphosphid [from chlorodiphenylphosphine (2.30 mL, 12.8 mmol) and lithium sand (0.350 g, 5.0 mmol)]; THF (50 mL); column chromatography (SiO_2 deactivated with Et_3N 5% in PE, 25 x 4 cm, PE / CH_2Cl_2 1:1) gave pure diphenyl(triferrocenylmethyl)phosphine (**59**) (0.733 g, 1.0 mmol, 25 %).

59: ^{1}H NMR (400 MHz, [d_6]-acetone): δ = 3.98 (s, 15H, CpH), 4.32 (s, 6H, CpR), 4.75 (br, 6H, CpR), 7.37 (m, 4H, Ph), 7.45 (m, 2H, Ph), 7.65 (m, 4H, Ph) ppm. - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 3.95 (s, 15H, CpH), 4.25 (s, 6H, CpR), 4.7 (br, 6H, CpR), 7.27 (m, 4H, Ph), 7.35 (m, 2H, Ph), 7.55 (m, 4H, Ph) ppm. - ^{13}C NMR (100 MHz, BB, HMQC, HMBC, $CDCl_3$): δ = 66.5 (*C*H-CpR), 69.6 (*C*H-CpH), 71.0 (*C*H-CpR), 93.0 (*C*R-CpR), 127.1 (d, J_{P-C} = 10.8 Hz, Ph), 130.9 (Ph), 133.0 (Ph), 134.2 (d, J_{P-C} = 8.2 Hz, Ph) ppm.* - ^{31}P NMR (121.5 MHz, $CDCl_3$): δ = 29.0 (PPh_2). - MS (ESI, ES^+) *m / z* (%) = 832 [$M+K^+$+CH_3CN], 567.01 [M^+–PPh_2].

* In the 13C NMR the signal corresponding to C-11 was not identified.

5.3.11 Diphenyl(2,2,2-triferrocenylethyl)phosphine (58)



$C_{44}H_{39}Fe_3P$
Mol. Wt.: 766.3

58

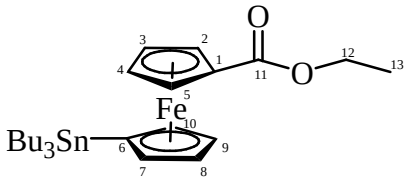
At 25 °C, a well stirred suspension of triferrocenylmethanol (**41**) (0.666 g, 1.1 mmol) in 50 mL of anhydrous DEE was treated with Ph_3CBF_4 (0.377 g, 1.1 mmol) and the solution was allowed to react until no starting material remained (TLC, CH_2Cl_2). The green precipitate was washed with 3 x 50 mL of anhydrous DEE, dissolved in 50 mL of anhydrous THF and cooled to –78 °C. To this solution lithiomethyldiphenylphosphine borane complex [from methyldiphenylphosphine borane complex (0.466 g, 2.1 mmol), *s*-BuLi (1.86 mL, 1.8 M in DEE, 1.0 mmol) and 9.32 mL of THF][130] was added.

The reaction mixture was allowed to warm to 25 °C and after 1 h, 40 mL of Et_2NH was added. The solution was stirred for 2 d. The volatiles were then removed at reduced pressure and anhydrous CH_2Cl_2 was added. Ammonium salts were removed by filtration through Celite, and the solvent was removed at reduced pressure to yield an orange solid, which was washed with cold degassed methanol, resulting in pure diphenyl(ethyl-2,2,2-triferrocenylethyl)phosphine (**58**) (0.616 g, 0.8 mmol, 70 %).

58: ^{1}H NMR (400 MHz, $CDCl_3$): δ = 3.6 (d, ^3J = 4.1 Hz, 2H, 12-H), 3.98 (s, 15H, CpH), 4.12 + 4.12 (AA'BB' line system, 2 x 6H, CpR), 7.2 - 7.4 (m, 10H, Ph) ppm. - ^{13}C NMR (100 MHz, BB, HMQC, HMBC, $CDCl_3$): δ = 40.4 (d, $^2J_{P\text{-}C}$ = 14.8 Hz, C-11), 48.4 (d, $^1J_{P\text{-}C}$ = 18.6 Hz, C-12), 66.3 (*C*H-CpR), 68.6 (d, $J_{P\text{-}C}$ = 5.3 Hz, *C*H-CpR), 69.0 (*C*H-CpH), 99.3 (d, $J_{P\text{-}C}$ = 3.8 Hz, *C*R-CpR), 128.1 (d, $J_{P\text{-}C}$ = 1.6 Hz, Ph), 133.1 (d, $J_{P\text{-}C}$ = 4.9 Hz, Ph), 141.1 (d, $J_{P\text{-}C}$ = 3.6 Hz, Ph), 128.0 (Ph) ppm. - ^{31}P NMR (121.5 MHz, $CDCl_3$): δ = –21.78 (PPh_2) ppm. - MS (ESI, ES^+): *m / z*: 767 [$M+H^+$], 783 [M^++O]. - HRMS (ESI) ($C_{44}H_{40}Fe_3P$): calcd. 767.0916; found 767.0912 [M+H].

5.4 1'-Triferrocenylmethane Derivatives

5.4.1 1-(Ethoxycarbonyl)-1'-(tributylstannyl)ferrocene (169)



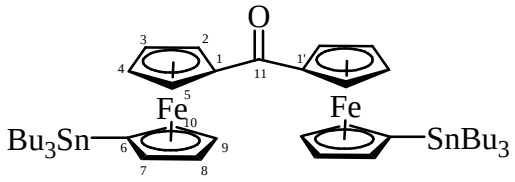
$C_{25}H_{40}FeO_2Sn$
Mol. Wt.: 547.1

169

At –78 °C a well stirred solution of 1,1'-bis(tributylstannyl)ferrocene (**168**)[100, 131] (2.000 g, 2.6 mmol) in 20 mL of anhydrous THF was treated with BuLi (1.50 mL, 1.6 M in pentane, 2.4 mmol). The reaction mixture was stirred for 1 h at –78 °C before freshly distilled ethyl chloroformate (0.25 mL, 2.6 mmol) was added. After stirring at –78 °C for 1h, hydrolysis was performed by addition of 20 mL of H_2O. The organic layer was washed with 3 x 20 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2, 25 x 4 cm, hexane / $CHCl_3$, 1:1) gave pure 1-(ethoxycarbonyl)-1'-(tributylstannyl)ferrocene (**169**) (1.136 g, 2.1 mmol, 79 %), as a red liquid.

169: IR (ATR): $\tilde{\nu}$ = 2957 cm^{-1} (m, CH), 2929 (m, CH), 2871 (m, CH), 1714 (m, C=O), 1459 (w, CH_3 or CH_2), 1376 (w, CH_3), 1274 (m), 1259 (m, C-O), 1131 (m, C-O), 1009 (s, Cp-H), 791 (s). - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.9 (t, ^3J = 7.3 Hz, 9H, $SnCH_2CH_2CH_2CH_3$), 1.02 - 1.04 (t, 6H, $SnCH_2CH_2CH_2CH_3$), 1.31 - 1.37 (m, 9H, $SnCH_2CH_2CH_2CH_3$, 13-H), 1.51 - 1.55 (m, 6H, $SnCH_2CH_2CH_2CH_3$), 4.25 (q, ^3J = 7.1 Hz, 2H, 12-H), 4.00 + 4.35 (AA'BB' line system, 2 x 2H, $CpSnBu_3$), 4.28 + 4.73 (AA'BB' line system, 2 x 2H, CpR) ppm. - ^{13}C NMR (100 MHz, BB, APT, HMQC, HMBC, $CDCl_3$): δ = 10.2 (+, $SnCH_2CH_2CH_2CH_3$), 13.7 (–, $SnCH_2CH_2CH_2CH_3$), 14.6 (–, C-13), 27.4 (+, $SnCH_2CH_2CH_2CH_3$), 29.1 (+, $SnCH_2CH_2CH_2CH_3$), 60.0 (+, C-12), 69.9 (–, *C*H-CpR), 70.6 (+, *C*R-$CpSnBu_3$), 71.1 (–, *C*H-CpR), 71.3 (+, *C*R-CpR), 72.6 (–, *C*H-$CpSnBu_3$), 75.9 (–, *C*H-$CpSnBu_3$), 171.6 (+, C-11) ppm. - MS (ESI, ES^+): *m / z*: 549 [$M+H^+$]. - HRMS (ESI) ($C_{25}H_{41}FeO_2Sn$): calcd. 549.1478; found 549.1473 [M+H]. - $C_{25}H_{40}FeO_2Sn$: calcd. C 54.88, H 7.37; found C 54.96, H 7.27.

5.4.2 Di[1'-(tributylstannyl)ferrocenyl]methanone (170)



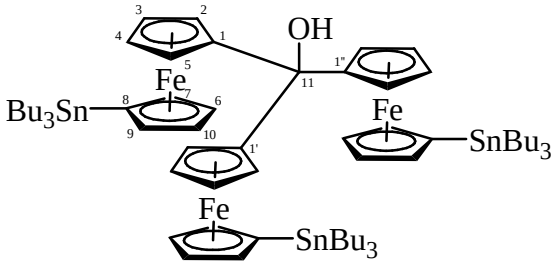
$C_{45}H_{70}Fe_2OSn_2$
Mol. Wt.: 976.1

170

At –78 °C a well stirred solution of 1,1'-bis(tributylstannyl)ferrocene (**168**)[100, 131] (1.700 g, 2.2 mmol) in 15 mL of anhydrous THF was treated with BuLi (1.6 M in hexane, 1.50 mL, 2.4 mmol). The reaction mixture was stirred for 1 h at –78 °C before freshly distilled ethyl chloroformate (0.10 mL, 1.1 mmol) was added. After stirring at –78°C for 1 h hydrolysis was performed by addition of 20 mL of H_2O. The organic layer was washed 3 x 20 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2, 25 x 4 cm, hexane / $CHCl_3$ 1:1), gave pure di[1'-(tributylstannyl)ferrocenyl]methanone (**170**) (0.560 g, 0.1 mmol, 55 %), as a red liquid.

170: IR (ATR): $\tilde{\nu}$ = 3086 cm^{-1} (w, Cp-H), 2954 (s), 2921 (s), 2870 (s), 2850 (s, CH), 1624 (s, C=O), 1456 (s, CH_3 or CH_2), 1375 (m, CH_3), 1287 (s, C-O). - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.9 (t, ^3J = 7.3 Hz, 2 x 9H, $SnCH_2CH_2CH_2CH_3$), 0.98 - 1.02 (t, 2 x 6H, $SnCH_2CH_2CH_2CH_3$), 1.29 - 1.38 (m, 2 x 6H, $SnCH_2CH_2CH_2CH_3$), 1.49 - 1.55 (m, 2 x 6H, $SnCH_2CH_2CH_2CH_3$), 4.01 + 4.33 (AA'BB' system, 2 x 4H, $CpSnBu_3$), 4.41 + 4.91 (AA'BB' system, 2 x 4H, CpR) ppm. - ^{13}C NMR (100 MHz, BB, APT, HMQC, HMBC, $CDCl_3$): δ = 10.3 (+, $SnCH_2CH_2CH_2CH_3$), 13.7 (–, $SnCH_2CH_2CH_2CH_3$), 27.4 (+, $SnCH_2CH_2CH_2CH_3$), 29.2 (+, $SnCH_2CH_2CH_2CH_3$), 70.4 (–, *C*H-CpR), 70.6 (+, *C*R-$CpSnBu_3$), 71.5 (–, *C*H-CpR), 73.1 (–, *C*H-$CpSnBu_3$), 76.0 (–, *C*H-$CpSnBu_3$), 80.3 (+, *C*R-CpR), 199.1 (+, C-11) ppm. - MS (ESI, ES^+): *m / z* = 979 [$M+H^+$]. - HRMS (ESI) ($C_{45}H_{71}Fe_2OSn_2$): calcd. 979.2248, found 979.2236. - $C_{45}H_{70}Fe_2OSn_2$: calcd. C 55.37, H 7.23; found C 54.78, H 7.113[M+H].

5.4.3 Tris[1'-(tributylstannyl)ferrocenyl]methanol (171)



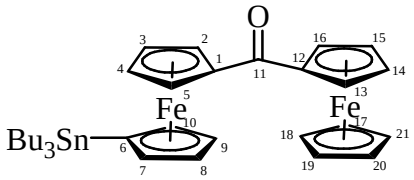
$C_{67}H_{106}Fe_3OSn_3$
Mol. Wt.: 1451.2

171

At –78 °C a well stirred solution of 1,1'-bis(tributylstannyl)ferrocene (**168**)[100, 131] (5.000 g, 6.5 mmol) in 20 mL of THF was treated with BuLi (4.00 mL, 1.6 M in pentane, 6.4 mmol). The reaction mixture was stirred for an additional 1 h at –78 °C before freshly distilled ethyl chloroformate (0.10 mL, 1.3 mmol) was added. After stirring at –78°C for 24 h, hydrolysis was performed by addition of 25 mL of H_2O. The organic layer was washed with 3 x 20 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2 deactivated with Et_3N 5% in PE, 25 x 4 cm, hexane), gave pure tris[1'-(tributylstannyl)ferrocenyl]methanol (**171**) (1.410 g , 1.0 mmol, 75 %), as a red liquid.

171: IR (ATR): $\tilde{\nu}$ = 3400 cm^{-1} (br, -OH), 3088 (w, Cp-H), 2954 (s, CH), 2922 (s, CH), 2870 (s, CH), 2851 (*s*, CH). - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.90 (t, ^3J = 7.3 Hz, 3 x 9H, $SnCH_2CH_2CH_2C\mathit{H}_3$), 0.97 - 1.01 (t, 3 x 6H, $SnC\mathit{H}_2CH_2CH_2CH_3$), 1.31 - 1.37 (m, 3 x 6H, $SnCH_2C\mathit{H}_2CH_2CH_3$), 1.51 - 1.56 (m, 3 x 6H, $SnCH_2CH_2C\mathit{H}_2CH_3$), 2.72 (s, 1H, O*H*), 4.00 + 4.03 (AA'BB' line system, 2 x 6H, CpR), 3.92 + 4.27 (AA'BB' line system, 2 x 6H, $CpSnBu_3$) ppm. - ^{13}C NMR (100 MHz, BB, DEPT, HMQC, HMBC, $CDCl_3$): δ = 10.2 (+, $Sn\mathit{C}H_2CH_2CH_2CH_3$), 13.7 (–, $SnCH_2CH_2CH_2\mathit{C}H_3$), 27.4 (+, $SnCH_2\mathit{C}H_2CH_2CH_3$), 29.2 (+, $SnCH_2CH_2\mathit{C}H_2CH_3$), 66.8 (–, *C*H-CpR), 67.2 (–, *C*H-CpR), 69.3 (+, *C*R-$CpSnBu_3$), 71.7 (–, +, *C*H-$CpSnBu_3$, C-11), 75.1 (–, CH-$CpSnBu_3$), 99.4 (+, *C*R-CpR) ppm. - $C_{67}H_{106}Fe_3OSn_3$: calcd. C 55.45, H 7.36; found C 56.89, H 7.819.

5.4.4 Assay of Acetalization of Di[1'-(tributylstannyl)ferrocenyl]methanone (170)



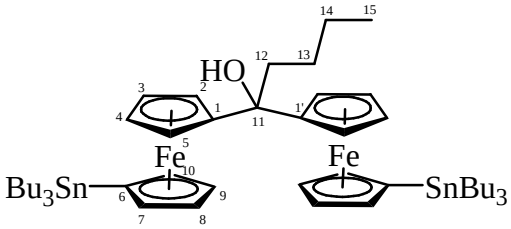
$C_{33}H_{44}Fe_2OSn$
Mol. Wt.: 687.10

173

A solution of di[1'-(tributylstannyl)ferrocenyl]methanone (**170**) (0.500 g, 0.5 mmol), ethylene glycol (21.00 mL, 376.0 mmol), and *para*-toluenesulfonic acid (few crystals) in 30 mL of toluene, was stirred for 12 h at reflux temperature. Hydrolysis was performed by addition of 20 mL of sat aqueous $NaHCO_3$, and the organic layer was washed with H_2O till neutral pH, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2, 25 x 4 cm): **I**: (hexane / $CHCl_3$ 8:2) gave pure (ferrocenyl)[1'-(tributylstannyl)ferrocenyl]methanone (**173**) (0.096 g, 0.1 mmol, 28%), as a red liquid. **II**: (hexane / $CHCl_3$ 1:1) gave pure diferrocenylketone (**40**) (0.111 g, 0.3 mmol, 55 %), identified by comparison with an authentic sample (^{1}H NMR).[129]

173: IR (ATR): $\tilde{\nu}$ = 3089 cm^{-1} (w, Cp-H), 2954 (s), 2923 (s), 2851 (s, CH), 1623 (s, C=O), 1459 (s, CH_3 or CH_2), 1377 (m, CH_3), 1288, 1260 (s, C-O). 1045, 1021 (s). - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.92 (t, ^3J = 7.3 Hz, 9H, $SnCH_2CH_2CH_2CH_3$), 1.01 - 1.04 (t, 6H, $SnCH_2CH_2CH_2CH_3$), 1.33 - 1.38 (m, 6H, $SnCH_2CH_2CH_2CH_3$), 1.53 - 1.58 (m, 6H, $SnCH_2CH_2CH_2CH_3$), 4.19 (s, 5H, CpH), 4.03 + 4.36 (AA'BB' line system, 2 x 2H, $CpSnBu_3$), 4.43 + 4.51 (AA'BB' line system, 2 x 2H, CpR), 4.94 + 4.99 (AA'BB' system, 2 x 2H, CpR) ppm. - ^{13}C NMR (100 MHz, BB, APT, HMQC, HMBC, $CDCl_3$): δ = 10.5 (+, $SnCH_2CH_2CH_2CH_3$), 13.9 (–, $SnCH_2CH_2CH_2CH_3$), 27.5 (+, $SnCH_2CH_2CH_2CH_3$), 29.3 (+, $SnCH_2CH_2CH_2CH_3$), 70.0 (–, CH-CpH), 70.4 (–, CH-CpR), 70.6 (–, CH-CpR), 71.4 (–, CH-CpR), 71.5 (–, CH-CpR), 73.2 (–, CH-$CpSnBu_3$), 74.4 (+, CR-$CpSnBu_3$), 76.1 (–, CH-$CpSnBu_3$), 80.2 (+, CR-CpR), 80.6 (+, CR-CpR), 199.2 (+, C-11) ppm. - MS (ESI, ES$^+$): *m / z* = 689 [M+H$^+$]. - HRMS (ESI) ($C_{33}H_{45}Fe_2OSn$): calcd. 689.1191, found 689.1218 [M+H].

5.4.5 1,1-Bis[1'-(tributylstannyl)ferrocenyl]pentan-1-ol (172)



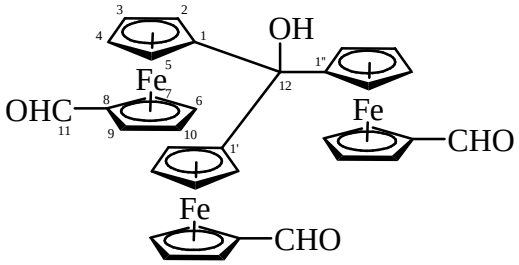
$C_{49}H_{80}Fe_2OSn_2$
Mol. Wt.: 1034.3

172

At –78 °C a well stirred solution of di[1,1'-(tributylstannyl)ferrocenyl]methanone (**170**) (0.411 g, 0.4 mmol) in 30 mL of THF was treated with BuLi (0.30 mL, 1.6 M in pentane, 0.5 mmol). After 1h at –78 °C, hydrolysis was performed by addition of 20 mL of H_2O. The organic layer was diluted with 20 mL of TBME, washed with 3 x 20 mL of H_2O, dried over $MgSO_4$ and the solvent was removed at reduced pressure. Column chromatography (SiO_2 deactivated with Et_3N 5% in PE, 25 x 4 cm, hexane / $CHCl_3$ 1:1), gave pure 1,1-bis[1'-(tributylstannyl)ferrocenyl]pentan-1-ol (**172**) (0.395 g, 0.4 mmol, 91 %), as a red liquid.

172: IR (ATR): $\tilde{\nu}$ = 3100 cm^{-1} (w, OH or Cp-H), 2956 (s), 2923 (s), 2871 (s), 2853 (s, CH), 1462 (w, CH_3 or CH_2), 1259 (m, CH_3), 1025 (s, =CH), 808 (s, Cp-H). - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.93 (t, ^3J = 7.3 Hz, 21H, $SnCH_2CH_2CH_2CH_3$ and 15-H), 1.01 - 1.05 (m, 12H, $SnCH_2CH_2CH_2CH_3$), 1.32 - 1.41 (m, 16H, $SnCH_2CH_2CH_2CH_3$ and 12-H or 13-H or 14-H and 12-H or 13-H or 14-H), 1.54 - 1.60 (m, 12H, $SnCH_2CH_2CH_2CH_3$), 2.06 - 2.10 (m, 2H, 12-H or 13-H or 14-H), 2.35 (s, 1H, O*H*), 3.98 (m, 2H, $CpSnBu_3$), 4.02 - 4.04 (m, 6H, $CpSnBu_3$ and CpR), 4.07 (m, 2H, CpR), 4.13 (m, 2H, CpR), 4.34 (m, 4H, $CpSnBu_3$) ppm. - ^{13}C NMR (100 MHz, BB, APT, HMQC, HMBC, $CDCl_3$): δ = 10.2 (+, $SnCH_2CH_2CH_2CH_3$), 13.7 (–, $SnCH_2CH_2CH_2CH_3$), 14.1 (–, $CH_2CH_2CH_2CH_3$), 23.3 (+, C-12 or C-13 or C-14), 26.4 (+, C-12 or C-13 or C-14), 27.4 (+, $SnCH_2CH_2CH_2CH_3$), 29.2 (+, $SnCH_2CH_2CH_2CH_3$), 43.6 (+, C-12 or C-13 or C-14), 66.3 (–, *C*H-CpR), 66.7 (–, *C*H-CpR), 66.9 (–, *C*H-CpR), 67.3 (–, *C*H-CpR), 69.4 (+, *C*R-$CpSnBu_3$), 71.3 (–, 2 x *C*H-$CpSnBu_3$), 71.8 (+, *C*R-CpR), 74.8 (–, *C*H-$CpSnBu_3$), 74.9 (–, *C*H-$CpSnBu_3$), 99.0 (s, C-11) ppm. - MS (ESI, ES^+): *m / z* = 1034 [M^+]. - HRMS (ESI) ($C_{49}H_{81}Fe_2OSn_2$): calcd. 1037.3030, found 1037.3069 [M+H].

5.4.6 Tris[1'-(formyl)ferrocenyl]methanol (174)



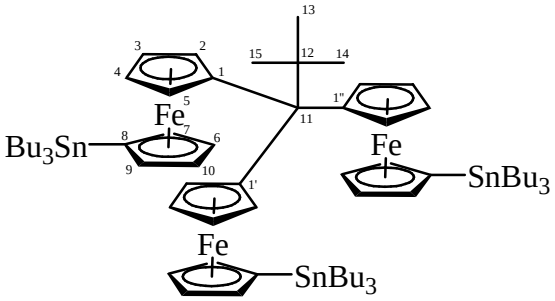
$C_{34}H_{28}Fe_3O_4$
Mol. Wt.: 668.1

174

At –78 °C a well stirred solution of tris[1'-(tributylstannyl)ferrocenyl]methanol (**171**) (0.523 g, 0.4 mmol) in 2 mL of THF was treated with BuLi (1.30 mL, 1.6 M in pentane, 2.1 mmol). The reaction mixture was stirred for 1 h at –78 °C and then an excess of DMF (8.00 mL, 103.0 mmol) was added. After stirring at –78 °C for 1 h, hydrolysis was performed by addition of 25 mL of H_2O. The organic layer was washed 3 x 20 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Crystallization from $CHCl_3$ / PE, gave pure tris[1'-(formyl)ferrocenyl]methanol (**174**) (0.062 g, 0.1 mmol, 26 %) as a red solid.

174: IR (ATR): $\tilde{\nu}$ = 3401 cm^{-1} (b, -OH), 3099 (w, Cp-H), 2956 (s), 2924 (s), 2853, (s, CH), 1678 (s, C=O). - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.78 (s, 1H, O*H*), 4.24 + 4.31 (AA'BB' line system, 2 x 6H, CpR), 4.47 + 4.70 (AA'BB' line system, 2 x 6H, CpCHO), 9.92 [s, 3H, 11-(11', 11'')] ppm. - ^{13}C NMR (100 MHz, BB, HMQC, HMBC, $CDCl_3$): δ = 68.3 (*C*H-CpR), 68.7 (*C*H-CpR), 69.0 (*C*R-CpR), 70.8 (*C*H-CpCHO), 74.3 (*C*H-CpCHO), 79.3 (*C*R-CpCHO), 100.8 (C-12), 194.0 [C-11(11', 11'')] ppm. - MS (ESI, ES^+): *m / z*: 690 [$M+Na^+$]. - HRMS (ESI) ($C_{34}H_{28}Fe_3O_4Na$): calcd. 690.9933; found 690.9946 [M+Na].

5.4.7 2,2-Dimethyl-1,1,1-tris[1'-(tributylstannyl)ferrocenyl]propane (175)



$C_{71}H_{114}Fe_3Sn_3$
Mol. Wt.: 1491.3

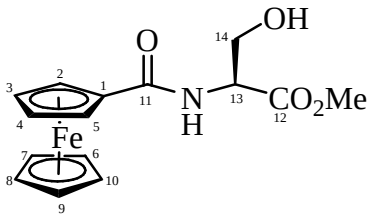
175

At 25 °C a well stirred solution of tris[1'-(tributylstannyl)ferrocenyl]methanol (**171**) (0.149 g, 0.1 mmol) in 20 mL of anhydrous THF was treated with Ph_3CBF_4 (0.074 g, 0.2 mmol). The solution was allowed to react until no starting material remained (TLC, CH_2Cl_2), and then the reaction mixture was cooled to –78 °C, and *tert*-butyllithium (0.20 mL, 1.7M in hexane, 0.1 mmol) was added. The reaction mixture was allowed to warm to 25 °C and after 1 h hydrolysis was performed by addition of 25 mL of H_2O. The organic layer was diluted with 25 mL of PE, washed with 3 x 25 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2, 25 x 2 cm, PE), gave pure 2,2-dimethyl-1,1,1-tris[1'-(tributylstannyl)ferrocenyl]propane (**175**) (0.054 g, 0.04 mmol, 36 %), as a red oil.

175: IR (ATR): $\tilde{\nu}$ = 3089 cm^{-1} (w, =CH), 2956 (s), 2926 (s), 2871 (s), 2854 (s, CH). - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.90 (t, ^3J = 7.3 Hz, 3 x 9H, $SnCH_2CH_2CH_2C\mathit{H}_3$), 0.97 - 1.01 (t, 3 x 6H, $SnC\mathit{H}_2CH_2CH_2CH_3$), 1.2 - 1.4 [m, 27H, $SnCH_2C\mathit{H}_2CH_2CH_3$, 13-(14, 15)-H], 1.5 - 1.6 (m, 3 x 6H, $SnCH_2CH_2C\mathit{H}_2CH_3$), 3.92 + 4.03 (AA'BB' line system, 2 x 6H, $CpSnBu_3$), 4.00 + 4.27 (AA'BB' line system, 2 x 6H, CpR) ppm. - ^{13}C NMR (100 MHz, BB, HMQC, HMBC, $CDCl_3$): δ = 10.4 (+, $Sn\mathit{C}H_2CH_2CH_2CH_3$), 13.7 (–, $SnCH_2CH_2CH_2\mathit{C}H_3$), 27.5 (+, $SnCH_2\mathit{C}H_2CH_2CH_3$), 29.2 (+, $SnCH_2CH_2\mathit{C}H_2CH_3$), 31.4 [–, C-13(14, 15)], 39.1 (+, C-11 or C-12), 50.2 (+, C-11 or C-12), 65.8 (–, *C*H-CpR), 68.4 (+, *C*R-$CpSnBu_3$), 70.2 (–, *C*H-CpR), 74.1 (–, *C*H-$CpSnBu_3$), 74.9 (–, *C*H-$CpSnBu_3$), 99.4 (+, *C*R-CpR) ppm. - $C_{71}H_{114}Fe_3Sn_3$: calcd. C 57.18, H 7.70; found C 57.29, H 7.449.

5.5 1,2-Triferrocenylmethane Derivatives

5.5.1 Methyl (*S*)-2-Ferrocenylamino-3-hydroxypropanoate (91)[65]



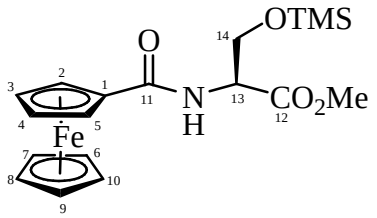
$C_{15}H_{17}FeNO_4$
Mol. Wt.: 331.1

(*S*)-**91**

At 0 °C, MeOH (50 mL, 1.2 mol) was treated with acetyl chloride (7.6 mL, 0.1 mol) over a period of 8 min. This solution was stirred for 5 min at 0 °C, then solid L-serine (**82**) (4.000 g, 38.0 mmol) was added in one portion, and the solution was slowly heated to reflux. Heating at reflux was continued for 2 h, then the solvent was removed at reduced pressure to give crude L-methyl serinate hydrochloride (**229**) as a white crystalline solid, which was used without further purification.[63]

At 25 °C, oxalyl chloride (4.80 mL, 56.7 mmol) was added to a suspension of ferrocenecarboxylic acid (**43**) (6.000 g, 26.0 mmol) in 60 mL of CH_2Cl_2 under N_2. A dark red homogeneous solution formed after 20 min. The reaction mixture was stirred for additional 20 min, followed by the removal of the solvent at reduced pressure. The resulting crude ferrocenoyl chloride (**193**) was dissolved in 60 mL of CH_2Cl_2 and added to the crude L-methyl serinate hydrochloride (**229**). Triethylamine (16.0 mL, 114.8 mmol) was added dropwise and the reaction was stirred for 1 h and then diluted with 250 mL of TBME. Hydrolysis was performed by addition of 25 mL of a 1M aqueous solution of NaOH. The organic phase was washed with 3 x 25 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2, 25 x 4 cm, EE) gave pure methyl (*S*)-2-ferrocenylamino-3-hydroxypropanoate (**91**) (6.888 g, 20.8 mmol, 80 %), identified by comparison with an authentic sample (^{1}H NMR).[65]

5.5.2 Methyl (*S*)-2-Ferrocenylamino-3-trimethylsilyloxypropanoate (230)



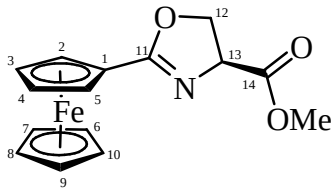
$C_{18}H_{25}FeNO_4Si$
Mol. Wt.: 403.3

(*S*)-**230**

A suspension of methyl (*S*)-2-ferrocenylamino-3-hydroxypropanoate (**91**) (0.730 g, 2.2 mmol), imidazol (0.365 g, 5.4 mmol) and Me_3SiCl (0.30 mL, 4.2 mmol) in 15 mL of anhydrous THF was stirred at 25 °C for 24 h. Hydrolysis was performed by addition of 20 mL of a saturated aqueous solution of $NaHCO_3$. The reaction mixture was diluted with 100 ml of TBME and the organic layer was washed with 3 x 25 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2, 25 x 2.5 cm, PE / EE 9:1) gave methyl (*S*)-2-ferrocenylamino-3-trimethylsilyloxypropanoate (**230**) as a red liquid (0.531 g, 1.3 mmol, 60 %).

(*S*)-230: ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.90 (s, 9H, $OSiMe_3$), 3.77 (s, 3H, CO_2Me), 3.87 (dd, ABX line system, ^3J = 3.3 Hz, $^2J_{gem}$ = 10.3 Hz, 1H, 14-H), 4.08 (dd, ABX line system, ^3J = 2.7 Hz, $^2J_{gem}$ = 10.2 Hz, 1H, 14-H), 4.23 (s, 5H, CpH), 4.34 (m, 2H, CpR), 4.67 (m, 1H, CpR), 4.75 (m, 1H, CpR), 4.78 (ddd, ^3J = ^3J = 2.9 Hz, ^3J = 8.4 Hz, 1H, 13-H), 6.52 (d, ^3J = 8.3 Hz, 1H, NH) ppm. - ^{13}C NMR (100 MHz, BB, HMBC, HMQC, $CDCl_3$): δ = – 0.7 [$Si(CH_3)_3$], 52.4 (CO_2Me), 53.9 (C-13), 62.9 (C-14), 68.0 (*C*H-CpR), 68.5 (*C*H-CpR), 69.8 (*C*H-CpH), 70.46 (*C*H-CpR), 70.54 (*C*H-CpR), 75.2 (*C*R-CpR), 170.2 (C-11), 171.0 (C-12) ppm.

5.5.3 Methyl (*S*)-2-Ferrocenyl-4,5-dihydrooxazole-4-carboxylate (86)[62, 64]



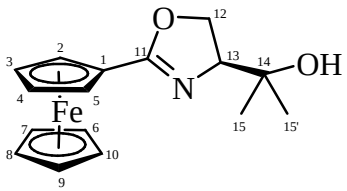
$C_{15}H_{15}FeNO_3$
Mol. Wt.: 313.1

(*S*)-**86**

At –78 °C a well stirred solution of methyl (*S*)-2-ferrocenylamino-3-hydroxypropanoate (**91**) (6.880 g, 20.8 mmol) in 200 mL of anhydrous CH_2Cl_2, was treated with DAST (2.70 mL, 20.4 mmol) and the colour of the mixture changed immediately from yellow-orange to dark-red. After stirring for 1 h at –78 °C, anhydrous K_2CO_3 (4.50 mL, 27.7 mmol) was added in one portion and the mixture was allowed to warm to 25 °C. The reaction mixture was poured into 200 mL of a saturated aqueous solution of $NaHCO_3$, and then extracted with 2 x 200 mL of CH_2Cl_2. The combined organic extracts were dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2, 25 x 4 cm, PE / EE 9:1, then EE) gave pure methyl (*S*)-2-ferrocenyl-4,5-dihydrooxazole-4-carboxylate (**86**) as a red solid (6.200 g, 19.8 mmol, 95 %), identified by comparison with an authentic sample (^{1}H NMR).[62, 64]

(*S*)-86: MS (ESI, ES^+): *m / z*: 314 [$M+H^+$]. - HRMS (ESI) ($C_{15}H_{16}FeNO_3$): calcd. 314.0480; found 314.0485 [M+H].

5.5.4 (*S*)-1-(2-Ferrocenyl-4,5-dihydrooxazol-4-yl)-1-methylethanol (88)[65]



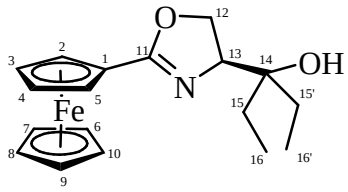
$C_{16}H_{19}FeNO_2$
Mol. Wt.: 313.2

(*S*)-**88**

At 0 °C a well stirred solution of methyl (*S*)-2-ferrocenyl-4,5-dihydrooxazole-4-carboxylate (**86**) (0.454 g, 1.4 mmol) in 40 mL of anhydrous THF was treated with MeMgBr (1.06 mL, 3

M in cyclohexane, 3.2 mmol). After 30 min at 0 °C, the reaction mixture was allowed to warm to 25 °C and after 30 min at 25 °C, hydrolysis was performed by addition of 200 mL of a saturated aqueous solution of NH_4Cl. The reaction mixture was diluted with 200 mL of TBME, and the organic layer was washed with 3 x 200 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2, 25 x 4 cm, PE / EE 9:1, then EE) gave pure (*S*)-1-(2-ferrocenyl-4,5-dihydrooxazol-4-yl)-1-methylethanol (**88**) (0.430 g, 1.4 mmol, 95 %), identified by comparison with an authentic sample (^{1}H NMR).[65]

5.5.5 (*S*)-1-(2-Ferrocenyl-4,5-dihydrooxazol-4-yl)-1-ethylpropanol (89)[65]

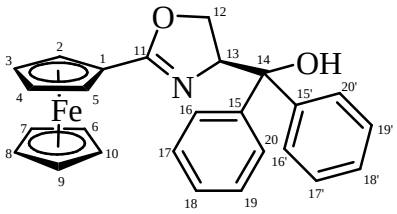


$C_{18}H_{23}FeNO_2$
Mol. Wt.: 341.2

(*S*)-**89**

At 0 °C a well stirred solution of methyl (*S*)-2-ferrocenyl-4,5-dihydrooxazole-4-carboxylate (**86**) (0.259 g, 0.8 mmol) in 20 mL of anhydrous THF was treated with EtMgBr (5.00 mL, 0.75 M in THF, 3.7 mmol). After 30 min at 0 °C, the reaction mixture was allowed to warm to 25 °C and after 30 min at 25 °C, hydrolysis was performed by addition of 20 mL of a saturated aqueous solution of NH_4Cl. The reaction mixture was diluted with 100 mL of TBME and the organic layer was washed with 3 x 25 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2, 25 x 2 cm, PE / EE 10:1) gave pure (*S*)-1-(2-ferrocenyl-4,5-dihydrooxazol-4-yl)-1-ethylpropanol (**89**) (0.254 g, 0.7 mmol, 90 %) identified by comparison with an authentic sample (^{1}H NMR).[65]

5.5.6 (*S*)-1-(2-Ferrocenyl-4,5-dihydrooxazol-4-yl)diphenylmethanol (90)[64]



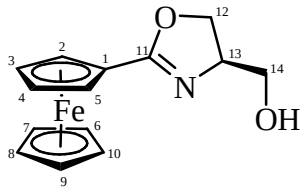
$C_{26}H_{23}FeNO_2$
Mol. Wt.: 437.3

(*S*)-**90**

At 0 °C a well stirred solution of methyl (*S*)-2-ferrocenyl-4,5-dihydrooxazole-4-carboxylate (**86**) (0.250 g, 0.8 mmol) in 20 mL of anhydrous THF was treated with PhLi (2.00 mL, 1.8 M in cyclohexane, 3.7 mmol). After 30 min at 0 °C, the reaction mixture was allowed to warm to 25 °C and after 30 min at 25 °C, hydrolysis was performed by addition of 20 mL of a saturated aqueous solution of NH_4Cl. The reaction mixture was diluted with 100 ml of TBME and the organic layer was washed with 3 x 25 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2, 25 x 2 cm, PE / EE 9:1) gave pure (*S*)-1-(2-ferrocenyl-4,5-dihydrooxazol-4-yl)diphenylmethanol (**90**) (0.190 g, 0.4 mmol, 54 %), identified by comparison with an authentic sample (^{1}H NMR).[64]

(*S*)-90: MS (ESI, ES^+): *m / z*: 438 [$M+H^+$]. - HRMS (ESI) ($C_{26}H_{24}FeNO_2$): calcd. 438.1156; found 438.1160 [M+H].

5.5.7 (*R*)-(2-Ferrocenyl-4,5-dihydrooxazol-4-yl)methanol (87)[65]



$C_{14}H_{15}FeNO_2$
Exact Mass: 285.0

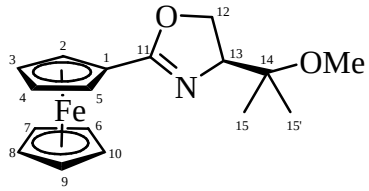
(*R*)-**87**

At 0 °C a well stirred solution of methyl (*S*)-2-ferrocenyl-4,5-dihydrooxazole-4-carboxylate (**86**) (0.249 g, 0.8 mmol) in 20 mL of anhydrous THF was treated with $LiAlH_4$ (0.210 g, 5.5 mmol). After 30 min at 0 °C, the reaction mixture was allowed to warm to 25 °C and after 30 min at 25 °C, hydrolysis was performed by addition of 20 mL of a saturated aqueous solution

of NH_4Cl. The reaction mixture was diluted with 100 ml of TBME and the organic layer was washed with 3 x 25 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2, 25 x 2 cm, MeOH) gave a red solid which was dissolved and filtered to give pure (*R*)-(2-ferrocenyl-4,5-dihydrooxazol-4-yl)methanol (**87**) (0.167 g, 0.6 mmol, 74 %) identified by comparison with an authentic sample (^{1}H NMR).[65]

(*R*)-87: MS (ESI, ES^+): *m / z*: 286 [$M+H^+$]. - HRMS (ESI) ($C_{14}H_{16}FeNO_2$): calcd. 286.0530; found 286.0526 [M+H].

5.5.8 (*S*)-2-Ferrocenyl-4-(1-methoxy-1-methylethyl)oxazoline (92)[65]



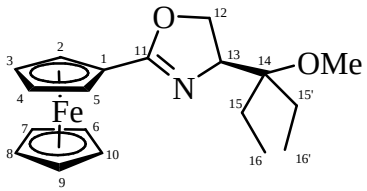
$C_{17}H_{21}FeNO_2$
Mol. Wt.: 327.2

(*S*)-**92**

To a suspension of (*S*)-1-(2-ferrocenyl-4,5-dihydrooxazol-4-yl)-1-methylethanol (**88**) (0.430 g, 1.4 mmol) and NaH (0.450 g, 60 % in mineral oil, 11.1 mmol) in 20 mL of anhydrous THF under nitrogen, MeI (0.40 mL, 6.4 mmol) was added and the reaction mixture was heated at reflux for 1 h under nitrogen. Hydrolysis was performed by addition of 20 mL of a saturated aqueous solution of $NaHCO_3$. The reaction mixture was diluted with 100 mL of TBME and the organic layer was washed with 3 x 25 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2, 25 x 2 cm, PE / EE 7:3) gave pure (*S*)-2-ferrocenyl-4-(1-methoxy-1-methylethyl)oxazoline (**92**) (0.309 g, 0.9 mmol, 69 %), identified by comparison with an authentic sample (^{1}H NMR).[65]

(*S*)-92: MS (ESI, ES^+): *m / z*: 328 [$M+H^+$]. - HRMS (ESI) ($C_{17}H_{22}FeNO_2$): calcd. 328.1000; found 328.0999 [M+H].

5.5.9 (*S*)-2-Ferrocenyl-4-(1-methoxy-1-ethylpropyl)oxazoline (93)[65]



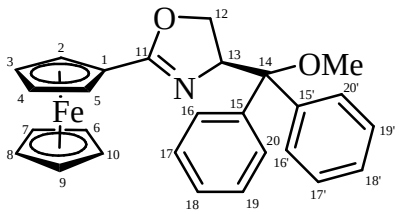
$C_{19}H_{25}FeNO_2$
Mol. Wt.: 355.3

(*S*)-**93**

To a suspension of (*S*)-1-(2-ferrocenyl-4,5-dihydrooxazol-4-yl)-1-ethylpropanol (**89**) (0.254 g, 0.7 mmol) and NaH (0.268 g, 60 % in mineral oil, 6.7 mmol) in 20 mL of anhydrous THF under nitrogen, MeI (0.30 mL, 4.8 mmol) was added and the reaction mixture was heated at reflux for 1 h under nitrogen. Hydrolysis was performed by addition of 20 mL of saturated aqueous solution of $NaHCO_3$. The reaction mixture was diluted with 100 ml of TBME and the organic layer was washed with 3 x 25 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2, 25 x 2 cm, PE / EE 8:2) gave pure (*S*)-2-ferrocenyl-4-(1-methoxy-1-ethylpropyl)oxazoline (**93**) (0.073 g, 0.2 mmol, 28 %), identified by comparison with an authentic sample (^{1}H NMR).[65]

(*S*)-93: MS (ESI, ES^+): *m / z*: 356 [$M+H^+$]. - HRMS (ESI) ($C_{19}H_{26}FeNO_2$): calcd. 356.1313; found 356.1325 [M+H].

5.5.10 (*S*)-2-Ferrocenyl-4-(1-methoxy-1,1diphenylmethyl)oxazoline (94)



$C_{27}H_{25}FeNO_2$
Mol. Wt.: 451.3

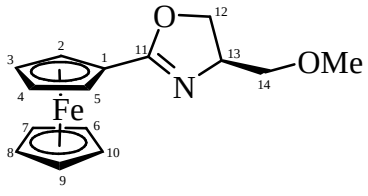
(*S*)-**94**

To a suspension of (*S*)-1-(2-ferrocenyl-4,5-dihydrooxazol-4-yl)diphenylmethanol (**90**) (0.190 g, 0.4 mmol) and NaH (0.268 g, 60 % in mineral oil, 7.0 mmol) in 20 mL of anhydrous THF under nitrogen, MeI (0.3 mL, 4.8 mmol) was added and the reaction mixture was heated

at reflux for 1 h under nitrogen. Hydrolysis was performed by addition of 20 mL of a saturated aqueous solution of $NaHCO_3$. The reaction mixture was diluted with 100 mL of TBME and the organic layer was washed with 3 x 25 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2, 25 x 2 cm, PE / EE 7:3) gave pure (*S*)-2-ferrocenyl-4-(1-methoxy-1,1diphenylmethyl)oxazoline (**94**) (0.130 g, 0.3 mmol, 66 %) as red crystals (*m.p.* 128 °C).

(*S*)-94: $[\alpha]^{D}_{20}$ = +220 (*c* = 0.55, $CHCl_3$). - IR (ATR): $\tilde{\nu}$ = 2962 cm^{-1} (w), 2922 (w), 2853 (w), 1732 (m), 1660 (m, C=N). 1013 (s, COC), 798 (s). - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 3.13 (s, 3H, OMe), 3.19 (s, 5H, CpH), 4.24 (m 2H, CpR), 4.33 (dd, ABX line system, $^2J_{gem}$ = 3.8 Hz, ^3J = 8.9 Hz, 2H, 12-H), 4.58 (m, 1H, CpR), 4.61 (m, 1H, CpR), 5.29 (dd, ABX line system, ^3J = ^3J = 9.52 Hz, 1H, 13-H), 7.2 - 7.45 (m, 10H, Ph) ppm. - ^{13}C NMR (100 MHz, BB, HMBC, HMQC, $CDCl_3$): δ = 51.9 (OMe), 68.4 (*C*H-CpR), 68.5 (C-12), 69.1 (*C*H-CpR), 69.4 (*C*H-CpH), 69.7 (*C*H-CpR), 69.9 (*C*H-CpR), 70.8 (C-13 or *C*R-CpR), 70.9 (C-13 or *C*R-CpR), 83.9 (C-14) 127.0 (Ph) 127.1(Ph) 127.3 (Ph) 127.8 (Ph) 128.7 (Ph), 129.1 (Ph), 141.3 (C-15 or C-15'), 143.2 (C-15 or C-15'), 166.9 (C-11) ppm. - MS (ESI, ES^+): *m / z*: 452 [M+H^+], 420 [M^+–OMe]. - HRMS (ESI) ($C_{27}H_{26}FeNO_2$): calcd. 452.1313; found 452.1311 [M+H]. - $C_{27}H_{25}FeNO_2$: calcd. C 71.85, H 5.58 N 3.10; found C 71.07, H 5.611 N 2.785.

5.5.11 (*R*)-2-Ferrocenyl-4-(1-methoxymethyl)oxazoline (95)[65]



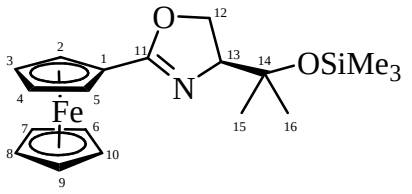
$C_{15}H_{17}FeNO_2$
Exact Mass: 299.1

(*R*)-**95**

To a suspension of (*S*)-(2-ferrocenyl-4,5-dihydrooxazol-4-yl)methanol (**87**) (0.167 g, 0.6 mmol) and NaH (0.191 g, 60 % in mineral oil, 5.0 mmol) in 20 mL of anhydrous THF under nitrogen, MeI (0.3 mL, 4.8 mmol) was added and the reaction mixture was heated at reflux for 1 h under nitrogen. Hydrolysis was performed by addition of 20 mL of a saturated aqueous solution of $NaHCO_3$. The reaction mixture was diluted with 100 mL of TBME and the

organic layer was washed with 3 x 25 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2, 25 x 2 cm, PE / EE 7:3) gave pure (*R*)-2-ferrocenyl-4-(1-methoxymethyl)oxazoline (**95**) (0.130 g, 0.4 mmol, 74 %), identified by comparison with an authentic sample (^{1}H NMR).[65]

5.5.12 (*S*)-2-Ferrocenyl-4-(1-trimethylsilyloxy-methylethyl)oxazoline (96)



$C_{19}H_{27}FeNO_2Si$
Mol. Wt.: 385.4

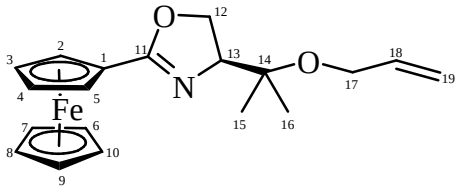
(*S*)-**96**

A suspension of (*S*)-1-(2-ferrocenyl-4,5-dihydrooxazol-4-yl)-1-methylethanol (**88**) (0.120 g, 0.4 mmol), imidazol (0.122 g, 1.8 mmol) and Me_3SiCl (0.10 mL, 0.8 mmol) in 15 mL of anhydrous THF was stirred at 25 °C for 24 h. Hydrolysis was performed by addition of 20 mL of a saturated aqueous solution of $NaHCO_3$. The reaction mixture was diluted with 100 mL of TBME and the organic layer was washed with 3 x 25 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2, 25 x 2.5 cm, PE / EE 9:1) gave pure (*S*)-2-ferrocenyl-4-(1-trimethylsilyloxy-methylethyl)oxazoline (**96**) (0.095 g, 0.2 mmol, 64 %) as a red liquid.

(*S*)-96: IR (ATR): $\tilde{\nu}$ = 2963 cm^{-1} (w), 2920 (w), 2851 (w), 1569 (s, C=N), 1261 (s), 1126 (s), 1086 (s), 1019 (s, SiOC), 793 (s, SiOC). - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.12 (s, 9H, TMS), 1.20 (s, 3H, 15-H or 16-H), 1.37 (s, 3H, 15-H or 16-H), 4.02 (dd, ABX line system, $^3J_{trans}$ = 7.2 Hz, $^3J_{cis}$ = 9.8 Hz, 1H, 13-H), 4.19 (s, 5H, CpH), 4.24 (dd, ABX line system, $^2J_{gem}$ = 8.8 Hz, $^3J_{cis}$ = 9.8 Hz, 1H, 12-H), 4.31 (m, 2H, CpR), 4.38 (dd, ABX line system, $^3J_{trans}$ = 7.28 Hz, $^2J_{gem}$ = 8.7 Hz, 1H, 12-H), 4.72 (m, 1H, CpR), 4.76 (m, 1H, CpR) ppm. - ^{13}C NMR (100 MHz, BB, HMBC, HMQC, $CDCl_3$): δ = 2.5 [$Si(CH_3)_3$], 24.3 (C-15 or C-16), 28.8 (C-15 or C-16), 68.7 (C-12), 68.9 (*C*H-CpR), 69.0 (*C*H-CpR), 69.4 (*C*H-CpH), 70.10 (*C*H-CpR), 70.12 (*C*H-CpR), 70.5, (*C*R-CpR), 74.9 (C-14), 76.2 (C-13), 167.0 (C-11) ppm. - MS (ESI,

ES^+): *m / z*: 386 [M+H^+]. - HRMS (ESI) ($C_{19}H_{28}FeNO_2Si$): calcd. 386.1239; found 386.1232 [M+H].

5.5.13 (*S*)-2-Ferrocenyl-4-(1-allyloxy-methylethyl)oxazoline (97)



$C_{19}H_{23}FeNO_2$
Mol. Wt.: 353.2

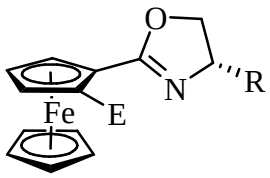
(*S*)-**97**

To a suspension of (*S*)-1-(2-ferrocenyl-4,5-dihydrooxazol-4-yl)-1-methylethanol (**88**) (0.134 g, 0.4 mmol) and NaH (0.400 g, 60 % in mineral oil, 10.0 mmol) in 40 mL of anhydrous THF under nitrogen, allylbromide (0.25 mL, 2.4 mmol) was added and the reaction mixture was heated at reflux for 3 h until no starting material remained (TLC, EE). Hydrolysis was performed by addition of 25 mL of a saturated aqueous solution of $NaHCO_3$. The reaction mixture was diluted with 25 mL of EE and the organic layer was washed with 3 x 25 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2, 25 x 4 cm, PE / EE 7:3) gave pure (*S*)-2-ferrocenyl-4-(1-allyloxy-methylethyl)oxazoline (**97**) (0.073 g, 0.2 mmol, 48 %).

(*S*)-97: $[\alpha]^D_{20}$ = +98 (*c* = 0.51, $CHCl_3$). - IR (ATR): $\tilde{\nu}$ = 3098 cm^{-1} (w, =CH), 3062 (w), 2976 (w), 2931 (w), 1646 (s, C=N). - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.15 (s, 3H, 15-H or 16-H), 1.35 (s, 3H, 15-H or 16-H), 3.9 (m, 2H, 17-H), 4.16 - 4.21 (m, ABX line system, 1H, 13-H), 4.18 (s, 5H, CpH), 4.27 (ddd, ABX line system, *J* = *J* = 9.9 Hz, 1H, 12-H), 4.32 (m, 2H, CpR), 4.43 (dd, *J* = 7.1 Hz, *J* = 8.5 Hz, 1H, 12-H), 4.71 (m, 1H, CpR), 4.76 (m, 1H, CpR), 5.11 (dd, ABX line system, *J* = 1.6 Hz, *J* = 10.4 Hz, 1H, 19-H), 5.25 (dd, ABX line system, *J* = 1.7 Hz, *J* = 17.2 Hz, 1H, 19-H), 5.89 (m, 1H, 18-H) ppm. - ^{13}C NMR (100 MHz, BB, APT, HMBC, HMQC, $CDCl_3$): δ = 20.0 (–, C-15 or C-16), 23.8 (–, C-15 or C-16), 62.9 (+, C-17), 68.4 (+, C-12), 68.9 (–, *C*H-CpR), 69.0 (–, *C*H-CpR), 69.5 (–, *C*H-CpH), 70.09 (–, *C*H-CpR), 70.13 (–, *C*H-CpR) 70.5 (+, *C*R-CpR), 74.4 (–, C-13), 76.4 (–, C-14), 115.5 (+, C-

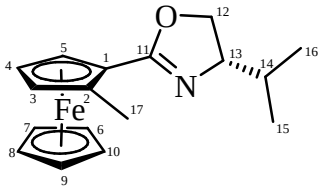
19), 135.8 (–, C-18), 166.9 (+, C-11) ppm. - MS (ESI, ES^+): *m / z*: 354 [$M+H^+$]. - HRMS (ESI) ($C_{19}H_{24}FeNO_2$): calcd. 354.1156; found 354.1147 [M+H].

5.5.14 General Procedure for the *ortho*-Functionalization of Ferrocenyloxazolines (GP2)



To a dark orange solution of (*S*)-2-ferrocenyl-4-isopropyloxazoline (**78**) and TMEDA at –78°C in anhydrous Et_2O, BuLi was added dropwise. After stirring at this temperature for 4 h the electrophile was added and the solution was allowed to warm to 25 °C over 14 h. H_2O was added and the reaction crude dissolved in EE. The organic layer was washed three times with 20 mL of water each and dried over $MgSO_4$. The solvent was removed under reduced pressure, giving the pure compound after recrystallization or column chromatography.

5.5.15 (*S*,*Rp*)-2-(2-Methylferrocenyl)-4-isopropyloxazoline (122)[55]

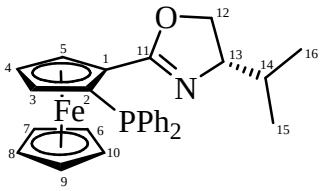


$C_{17}H_{21}FeNO$
Mol. Wt.: 311.2

(*S*,*Rp*)-**122**

GP2: (*S*)-2-ferrocenyl-4-isopropyloxazoline (**78**) (0.500 g, 1.7 mmol); TMEDA (0.33 mL, 2.2 mmol); Et_2O (6.25 mL); BuLi (1.40 mL, 1.6 M in hexane, 2.2 mmol); MeI (0.15 mL, 2.4 mmol); column chromatography (SiO_2, 25 x 4 cm, PE / CH_2Cl_2 3:1) gave pure (*S*,*Rp*)-2-(2-methylferrocenyl)-4-isopropyloxazoline (**122**) (0.462 g, 1.5 mmol, 88 %, > 95 % *de*), identified by comparison with an authentic sample (^{1}H NMR).[55]

5.5.16 (*S,Sp*)-2-(2-Diphenylphosphanylferrocenyl)-4-isopropyloxazoline (121)[53]

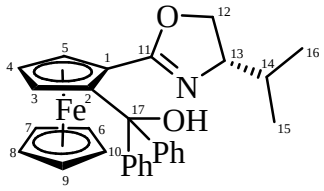


$C_{28}H_{28}FeNOP$
Mol. Wt.: 481.3

(*S,Sp*)-**121**

GP2: (*S*)-2-ferrocenyl-4-isopropyloxazoline (**78**) (0.500 g, 1.7 mmol); TMEDA (0.33 mL, 2.2 mmol); Et_2O (6.25 mL); BuLi (1.50 mL, 1.6 M in hexane, 2.4 mmol); Ph_2PCl (0.9 mL, 5.0 mmol); column chromatography (SiO_2, 25 x 4 cm, PE / CH_2Cl_2 5:1) gave pure (*S,Sp*)-2-(2-diphenylphosphanylferrocenyl)-4-isopropyloxazoline (**121**) (0.584 g, 1.2 mmol, 72 %, > 95 % *de*), identified by comparison with an authentic sample (^{1}H NMR).[53]

5.5.17 (*S,Rp*)-2-(2-Diphenylhydroxymethylferrocenyl)-4-isopropyloxazoline (128)



$C_{29}H_{29}FeNO_2$
Exact Mass: 479.2

(*S,Rp*)-**128**

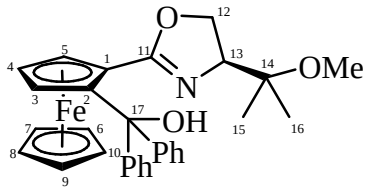
GP2: (*S*)-2-ferrocenyl-4-isopropyloxazoline (**78**) (0.504 g, 1.7 mmol); TMEDA (0.33 mL, 2.2 mmol); Et_2O (6.25 mL); BuLi (1.40 mL, 1.6 M in hexane, 2.2 mmol); benzophenone (0.309 g, 1.7 mmol); column chromatography (SiO_2 deactivated with a 5% Et_3N solution in PE, 25 x 4 cm, PE / CH_2Cl_2 10:1) gave pure (*S,Rp*)-2-(2-diphenylhydroxymethylferrocenyl)-4-isopropyloxazoline (**128**) (0.777 g, 1.6 mmol, 96 %, > 95 % *de*) as a yellow-red solid. Recrystallization from hexane gave crystals (*m.p.* 135 °C) of (*S,Rp*)-**128** (0.511 g, 1.1 mmol, 63 %, > 95 % *de*).

(*S,Rp*)-128: $[\alpha]^D_{20} = -366$ (*c* = 0.12, $CHCl_3$). - IR (ATR): $\tilde{\nu}$ = 3154 cm^{-1} (w, OH), 3056 (w, Cp-H), 2954 (w), 2873 (w), 1650 (s, C=N). - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.98 (d, ^3J = 6.8 Hz, 3H, 15-H or 16-H), 1.05 (d, ^3J = 6.7 Hz, 3H, 15-H or 16-H), 1.83 - 1.75 (m, 1H, 14-

H), 3.67 - 3.61 (ddd, ABX line system, ^3J = 6.4 Hz, $^3J_{trans}$ = 8.4 Hz, $^3J_{cis}$ = 9.8 Hz, 1H, 13-H), 3.72 (dd, *J* = 1.6 Hz, *J* = 2.5 Hz, 1H, CpR), 3.98 (dd, ABX line system, , $^3J_{trans}$ = $^2J_{gem}$ = 8.3 Hz, 1H, 12-H), 4.17 (dd, ABX line system, $^2J_{gem}$ = 8.4 Hz, $^3J_{cis}$ = 9.8 Hz, 1H, 12-H), 4.27 (t, *J* = 2.5 Hz, 1H, CpR), 4.28 (s, 5H, CpH), 4.76 (dd, *J* = 1.6 Hz, *J* = 2.5 Hz, 1H, CpR), 7.14 - 7.18 (m, 5H, Ph), 7.24 - 7.36 (m, 3H, Ph), 7.53 - 7.55 (m, 2H, Ph), 9.3 (s, 1H, OH) ppm. - ^{13}C NMR (100 MHz, BB, DEPT, $CDCl_3$): δ = 18.6 (C-15 or C-16), 18.8 (C-15 or C-16), 32.4 (C-14), 66.0, 67.9, 70.0, 70.4, 70.6 (*C*H-CpH), 71.5, 74.9, 77.21, 100.5 (C-17) 126.2 (Ph), 126.5 (Ph), 127.0 (Ph), 127.1 (Ph), 127.4 (Ph), 127.8 (Ph), 146.4 (Ph), 149.2 (Ph), 167.5 (C-11) ppm. - MS (ESI, ES^+): *m / z*: 462 [M^+–OH], 480 [M+H^+]. - HRMS (ESI) ($C_{29}H_{30}FeNO_2$): calcd. 480.1626; found 480.1606 [M+H]. - $C_{29}H_{29}FeNO_2$: calcd. C 72.66, H 6.10 N 2.92; found C 72.33, H 5.95 N 2.80.

Crystal Structure Analysis of (*S,Rp*)-**128:** $C_{29}H_{29}FeNO_2$, molecular weight, 3835.06 g / mol, temperature 295 K, crystal system tetragonal, space group P4(1)2(1)2 (No.92), *a* = 11.851(3), *b* = 11.851(3), *c* = 35.173(15) Å, α = 90°, β = 90°, γ = 90°, *V* = 4940(3) $Å^3$, *Z* = 8, $\rho_{calcd.}$ = 1.289 g cm^{-3}, *F*(000) = 2016, Absorption coefficient = 0.636 mm^{-1}, crystal size 0.50 x 0.14 x 0.14 mm, Stoe IPDS area detector diffractometer, θ-range = 1.81 to 24.24°, limiting indices –13<=h<=13, –13<=k<=13, –40<=l<=40, reflections collected / unique 53815 / 3979 [*R*(int) = 0.1239], completeness of data(θ = 24.24): 99.5%, no absorption correction, no extinction correction, refinement method Full-matrix least-squares on F^2, goodness-of-fit on F^2 = 0.525, R_1 = 0.0288, wR_2 = 0.0601 (I>2 σ (I)), R-indices[all data]: R_1 = 0.0770, wR_2 = 0.0774, minimal and maximal residual electron density –0.162/0.147 $eÅ^{-3}$.

5.5.18 (*S*,*Rp*)-2-(2-Diphenylhydroxymethylferrocenyl)-4-(1-methoxy-1-methylethyl)-oxazoline (124)



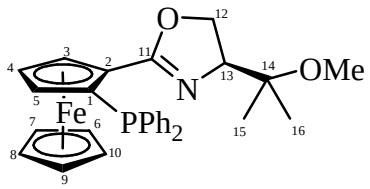
$C_{30}H_{31}FeNO_3$
Mol. Wt.: 509.4

(*S*,*Rp*)-**124**

GP2: (*S*)-2-ferrocenyl-4-(1-methoxy-1-methylethyl)oxazoline (**92**) (0.174 g, 0.5 mmol); TMEDA (0.10 mL, 0.7 mmol); Et_2O (2.00 mL); BuLi (0.44 mL, 1.6 M in hexane, 0.7 mmol); benzophenone (0.206 g, 1.1 mmol); column chromatography (SiO_2 deactivated with a 5% Et_3N solution in PE, 25 x 4 cm, PE / CH_2Cl_2 10:1) gave pure (*S*,*Rp*)-2-(2-diphenylhydroxymethylferrocenyl)-4-(1-methoxy-1-methylethyl)-oxazoline (**124**) (0.170 g, 0.3 mmol, 63 %, > 95 % *de*) as a yellow-red solid. Recrystallization from hexane gave yellow-red crystals (*m.p.* 143 °C) of (*S*,*Rp*)-**124.**

(*S*,*Rp*)-124: $[\alpha]^{D}_{20}$ = +328 (*c* = 0.36, $CHCl_3$). - IR (ATR): $\tilde{\nu}$ = 3095 cm^{-1} (w, OH), 3076 (w, =CH), 2962 (w), 2931 (w), 2828 (w), 1650 (s, C=N). - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.29 (s, 3H, 15-H or 16-H), 1.34 (s, 3H, 15-H or 16-H), 3.30 (s, 3H, OMe), 3.76 (dd, ^3J = ^4J = 1.7 Hz, 1H, CpR), 3.88 (dd, ABX line system, *J* = 8.2 Hz, *J* = 9.9 Hz, 1H, 13-H), 4.18 (dd, ABX line system, ^3J = ^2J = 9.9 Hz, 1H, 12-H), 4.32 (dd, ^3J = ^4J = 2.5 Hz, 1H, CpR), 4.37 (s, 5H, CpH), 4.38 (dd, ABX line system, *J* = *J* = 8.5 Hz, 1H, 12-H), 4.82 (dd, ^3J = ^4J = 2.4 Hz, 1H, CpR), 7.20 (m, 5H, Ph), 7.31 (m, 1H, Ph), 7.36 - 7.40 (m, 2H, Ph), 7.57 - 7.59 (m, 2H, Ph), 9.23 (s, 1H, OH) ppm. - ^{13}C NMR (100 MHz, BB, HMQC, HMBC, $CDCl_3$): δ =20.5 (C-15 or C-16), 22.7 (C-15 or C-16), 49.5 (OMe), 65.6 (*C*R-CpR), 68.0 (*C*H-CpR), 68.3 (C-12), 70.4 (*C*H-CpR), 70.6 (*C*H-CpH), 75.0 (*C*H-CpR), 75.4 (C-14), 73.7 (C-13), 77.3 (C-17), 101 (*C*R-CpR), 126.2 (Ph), 126.5 (Ph), 127.0 (Ph), 127.1 (Ph), 127.3 (Ph), 127.8 (Ph), 146.3 (Ph), 149.1 (Ph), 158.4 (C-11) ppm. - MS (ESI, ES^+): *m* / *z*: 492 [M^+–OH], 510 [M+H^+], 532 [M+Na^+]. - HRMS (ESI) ($C_{30}H_{32}FeNO_3$): calcd. 510.1732; found 510.1732 [M+H]. - $C_{30}H_{31}FeNO_3$: calcd. C 70.73, H 6.13 N 2.75; found C 70.64, H 6.094 N 2.692.

5.5.19 (*S*,*Sp*)-2-(2-Diphenyphosphanylferrocenyl)-4-(1-methoxy-1-methylethyl)oxazoline (123)



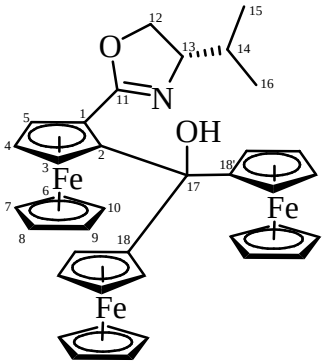
$C_{29}H_{30}FeNO_2P$
Exact Mass: 511.1

(*S*,*Sp*)-**123**

GP2: (*S*)-2-ferrocenyl-4-(1-methoxy-1-methylethyl)oxazoline (**92**) (0.309 g, 0.9 mmol); TMEDA (0.17 mL, 1.2 mmol); Et_2O (3.60 mL); BuLi (0.80 mL, 1.6 M in hexane, 1.28 mmol); Ph_2PCl (0.40 mL, 2.2 mmol); column chromatography (SiO_2, 25 x 2 cm, EE followed by EE / Et_3N 20:1) gave pure (*S*,*Sp*)-2-(2-diphenyphophanylferrocenyl)-4-(1-methoxy-1-methylethyl)oxazoline (**123**) (0.151 g, 0.3 mmol, 31 %, > 95 % *de*) as a red liquid.

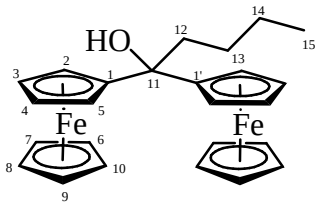
(***S*,*Sp*)-123:** $[\alpha]^{D}_{20}$ = –62.5 (*c* = 0.176, $CHCl_3$). - IR (ATR): $\tilde{\nu}$ = 3075 cm^{-1} (w, =CH), 2970 (w), 2925 (w), 2828 (w), 1618 (s, C=N). - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.87 ppm (s, 3H, 15-H or 16-H), 1.12 (s, 3H, 15-H or 16-H), 3.14 (s, 3H, OMe), 3.79 (dd, ABX line system, *J* = *J* = 8.0 Hz, 1H, 12-H), 3.86 (m, 1H, CpR), 3.90 (dd, ABX line system, *J* = *J* = 8.0 Hz, 1H, 13-H), 4.15 (dd, ABX line system, *J* = *J* = 9.1 Hz, 1H, 12-H), 4.42 (m, 1H, CpR), 4.46 (s, 5H, CpH), 5.0 (m, 1H, CpR), 7.34 - 7.44 (m, 6H, Ph), 7.60 - 7.65 (m, 2H, Ph), 7.80 - 7.75 (m, 2H, Ph) ppm. - ^{13}C NMR (100 MHz, BB, HMQC, HMBC, $CDCl_3$): δ = 18.9 (C-15 or C-16), 22.4 (C-15 or C-16), 49.4 (OMe), 68.6 (C-12), 71.16 (*C*H-CpH), 71.3 (*C*H-CpR), 73.7 (*C*H-CpR), 73.8 [*C*R-CpR(C-2)], 74.0 (C-13), 74.2 [d, $J_{P\text{-}C}$ = 16.7 Hz, *C*R-CpR(C-1)], 76.3 (C-14), 78.4 (d, $J_{P\text{-}C}$ = 14.5 Hz, *C*H-CpR), 127.8 (d, $J_{P\text{-}C}$ = 7.2 Hz, Ph), 128.0 (d, $J_{P\text{-}C}$ = 6.7 Hz, Ph), 130.7 (d, $J_{P\text{-}C}$ = 2.7 Hz, Ph), 131.0 (d, $J_{P\text{-}C}$ = 2.5 Hz, Ph), 131.1 (d, $J_{P\text{-}C}$ = 9.7 Hz, Ph), 131.5 (d, $J_{P\text{-}C}$ = 9.1 Hz, Ph), 134.1 (d, $J_{P\text{-}C}$ = 11.4 Hz, Ph), 135.2 (d, $J_{P\text{-}C}$ = 16.4 Hz, Ph), 164.5 (C-11) ppm. - ^{31}P NMR (121.5 MHz, $CDCl_3$): δ = 27.4 (PPh_2) ppm. - MS (ESI, ES^+): *m* / *z*: 528 [M+O+H^+], 512 [M+H^+], 550 [M+O+Na^+]. - HRMS (ESI) ($C_{29}H_{31}FeNO_2$): calcd. 512.1442; found 512.1453 [M+H].

5.5.20 (*S,Rp*)-2-(2-Diferrocenylhydroxymethylferrocenyl)-4-isopropyloxazoline (129)



(*S,Rp*)-**129**

$C_{37}H_{37}Fe_3NO_2$
Mol. Wt.: 695.2



131

$C_{25}H_{28}Fe_2O$
Exact Mass: 456.1

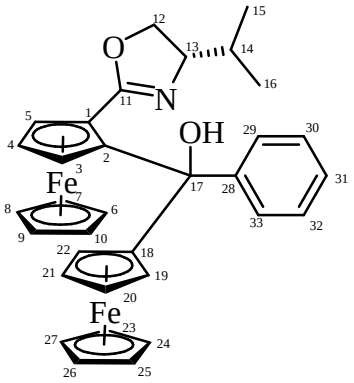
GP2: (*S*)-2-ferrocenyl-4-isopropyloxazoline (**78**) (0.503 g, 1.7 mmol); TMEDA (0.33 mL, 2.2 mmol); Et_2O (6.25 mL); BuLi (1.40 mL, 1.6 M in hexane, 2.2 mmol); diferrocenylketone (**40**) (0.678 g, 1.7 mmol) solution in 20 mL of anhydrous THF; column chromatography (SiO_2 deactivated with Et_3N 5% in PE, 25 x 4 cm, PE / CH_2Cl_2 10:1) gave (*S,Rp*)-2-(2-diferrocenylhydroxymethylferrocenyl)-4-isopropyloxazoline (**129**) (0.718 g, 1.0 mmol, 61 %, > 95 % *de*) as a red liquid. Crystallization from TBME gave pure 1,1-bisferrocenylpentan-1-ol (**131**) (0.154 g, 0.3 mmol, 24 %) as yellow crystals and pure (*S,Rp*)-**129** (0.564 g, 0.8 mmol, 48 %, > 95 % *de*) as a yellow foam (*m.p.* 136 °C).

(*S,Rp*)-129: $[\alpha]^{D}_{20}$ = +94 (*c* = 0.10, $CHCl_3$). - IR (ATR): $\tilde{\nu}$ = 3095 cm^{-1} (w, OH), 2958 (w), 1650 (s, C=N), 814 (s). - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.09 (d, ^3J = 6.8 Hz, 3H, 15-H or 16-H), 1.15 (d, ^3J = 6.8 Hz, 3H, 15-H or 16-H), 2.12 - 1.98 (m, 1H, 14-H), 3.88 (s, 5H, CpH), 3.89 (m, 1H, CpR), 3.95 (m, 1H, CpR), 4.04 (s, 5H, CpH), 4.05 (m, 1H, CpR), 4.07 (s, 5H, CpH), 4.09 (m, 2H, 2 x CpR), 4.16 (m, 2H, 2 x CpR), 4.16 (m, ABX line system, 2H, 12-H), 4.26 (m, 1H, CpR), 4.34 (m, ABX line system, 1H, 13-H), 4.63 (m, 1H, CpR), 4.72 (m, 1H, CpR), 4.75 (m, 1H, CpR), 8.95 (s, 1H, OH) ppm. - ^{13}C NMR (100 MHz, BB, HMQC, HMBC, $CDCl_3$): δ = 18.0 (C-15 or C-16), 19.2 (C-15 or C-16), 32.0 (C-14), 64.8 (*C*R-CpR), 65.8 (*C*H-CpR), 65.9 (*C*R-CpR), 66.2 (*C*H-CpR), 66.5 (*C*H-CpR), 66.7 (CH-CpR), 67.6 (*C*H-CpR), 67.8 (*C*H-CpR), 68.1 (*C*H-CpR), 68.4 (*C*H-CpR), 68.5 (*C*H-CpH), 69.0 (*C*H-CpH),

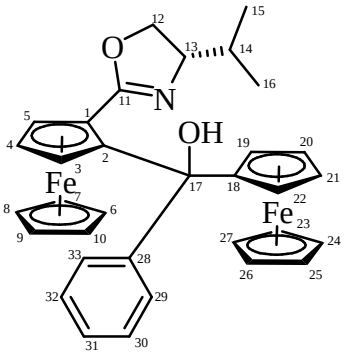
69.4 (C-13), 69.9 (*C*H-CpR), 70.8 (*C*H-CpH), 72.0 (C-12), 72.2 (*C*H-CpR), 73.5 (*C*H-CpR), 100.0 (*C*R-CpR), 100.3 (C-17), 101.1 (*C*R-CpR), 168.5 (C-11) ppm. - MS (ESI, ES^+): *m / z*: 678 [M^+–OH], 695 [M^+]. - HRMS (ESI) ($C_{37}H_{37}Fe_3NO_2$): calcd. 695.0872; found 695.0897 [M]. - $C_{37}H_{37}Fe_3NO_2$: calcd. C 63.92, H 5.36 N 2.01; found C 64.37, H 5.567 N 1.919.

Crystal Structure Analysis of **131:** $C_{50}H_{56}Fe_4O_2$, molecular weight, 912.38 g / mol, temperature 295 K, crystal system triclinic, space group P^{-1}, *a* = 9.748(3), *b* = 10.761(3), *c* = 11.494(3) Å, α = 68.52(3)°, β = 88.34(3)°, γ = 68.39(3)°, *V* = 1035.3(5) $Å^3$, *Z* = 1, $\rho_{calcd.}$ = 1.463 g cm^{-3}, *F*(000) = 476, Absorption coefficient = 1.414 mm^{-1}, crystal size 0.22 x 0.17 x 0.09 mm, Stoe IPDS area detector diffractometer, θ-range = 2.20 to 26.20°, limiting indices –12<=h<=11, –13<=k<=13, –14<=l<=14, reflections collected / unique 14727 / 3793 [*R*(int) = 0.1393], completeness of data(θ = 26.20): 91.0%, no absorption correction, no extinction correction, refinement method Full-matrix least-squares on F^2, goodness-of-fit on F^2 = 0.724, R_1 = 0.0602, wR_2 = 0.1554 (I>2 σ (I)), R-indices[all data]: R_1 = 0.1566, wR_2 = 0.2358, minimal and maximal residual electron density – 0.732 / 0.488 e$Å^{-3}$.

5.5.21 (*S,R,Rp*)-2-(2-Ferrocenylphenylhydroxymethylferrocenyl)-4-isopropyloxazoline (130) and (*S,S,Rp*)-2-(2-Ferrocenylphenylhydroxymethylferrocenyl)-4-isopropyl-oxazoline (130)



(*S,S,Rp*)-**130**



$C_{33}H_{33}Fe_2NO_2$
Mol. Wt.: 587.3

(*S,R,Sp*)-**130**

GP2: (*S*)-2-ferrocenyl-4-isopropyloxazoline (**78**) (0.507 g, 1.7 mmol); TMEDA (0.33 mL, 2.2 mmol); Et_2O (2.5 mL); BuLi (1.40 mL, 1.6 M in hexane, 2.2 mmol);

ferrocenylphenylketone (0.493 g, 1.7 mmol) solution in 20 mL of anhydrous THF; column chromatography (SiO_2, deactivated with Et_3N 5% in PE, 25 x 4 cm, PE / EE 9:1) gave a 3:1 mixture of diastereoisomers (*S,R,Rp*)-2-(2-ferrocenylphenylhydroxymethyl-ferrocenyl)-4-isopropyloxazoline (**130**) and (*R,S,Rp*)-2-(2-ferrocenylpheny-lhydroxymethyl-ferrocenyl)-4-isopropyloxazoline (**130**) (0.802 g, 1.4 mmol, 80 %, > 95 % *de*) as a red oil. Recrystallization from TBME gave a 2.5:1 mixture of diastereoisomers (0.491 g, 0.8 mmol, 49 %, > 95 % *de*) as yellow crystals (*m.p.* 149 - 152 °C).

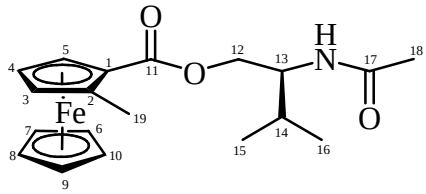
(*S,S,Rp*)-130 and (*S,R,Rp*)-130: $[\alpha]^{D}_{20} = -24$ (*c* = 0.20, $CHCl_3$) - IR (ATR): $\tilde{\nu}$ = 3095 cm^{-1} (w, OH), 2961 (w), 2928 (w), 2871 (w), 1648 (s, C=N). - MS (ESI, ES^+): *m / z*: 570 [M^+–OH], 588 [$M+H^+$]. - HRMS (ESI) ($C_{33}H_{32}Fe_2NO$): calcd. 570.1183; found 570.1171 [M–OH]. - $C_{33}H_{33}Fe_2NO_2$: calcd. C 67.49, H 5.66 N 2.38; found C 67.48, H 5.47 N 2.13.

(*S,S,Rp*)-130 or (*S,R,Rp*)-130: ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.99 (d, ^3J = 6.8 Hz, 3H, 15-H or 16-H), 1.10 (d, ^3J = 6.6 Hz, 3H, 15-H or 16-H), 1.8 - 1.9 (m, 1H, 14-H), 3.62 (ddd, ABX line system, *J* = 6.5 Hz, *J* = 9.4 Hz, *J* = 15.9 Hz, 1H, 13-H), 3.66 (s, 1H, CpR), 3.88 (m, ABX line system, 1H, 12-H), 3.90 (m, 1H, CpR), 4.04 (s, 5H, CpH), 4.06 (d, 1H, *J* = 1.4 Hz, CpR), 4.10 (m, 1H, 12-H), 4.16 (dd, *J* = *J* = 2.6 Hz, 1H, CpR), 4.25 (s, 5H, CpH), 4.27 (m, 1H, CpR), 4.54 (dd, 1H, *J* = 1.6 Hz, *J* = 2.4 Hz, CpR), 4.71 (dd, *J* = *J* = 1.1 Hz, 1H, CpR), 7.10 - 7.50 (m, 4H, Ph), 7.78 (d, *J* = 7.2 Hz, 1H, Ph), 8.71 (s, 1H, OH) ppm. - ^{13}C NMR (100 MHz, BB, $CDCl_3$): δ = 18.6 (C-15 or C-16), 19.3 (C-15 or C-16), 32.4 (C-14), 65.1 [*C*R-CpR(C-18)], 66.9 (*C*H-CpR), 67.0 (*C*H-CpR), 67.1 (*C*H-CpR), 67.3 (*C*H-CpR), 68.4 (*C*H-CpR), 68.8 (*C*H-CpH), 69.77 (*C*H-CpR), 69.84 (C-12), 70.6(*C*H-CpH), 71.7 (C-13), 74.12 (*C*H-CpR), 74.3 [*C*R-CpR(C-2)], 96.63 (C-17), 102.8 [*C*R-CpR(C-1)], 126.4 (Ph), 126.8 (Ph), 127.7 (Ph), 147.6 (Ph), 170.4 (C-11) ppm.

(*S,S,Rp*)-130 or (*S,R,Rp*)-130: ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.1 (d, ^3J = 6.6 Hz, 3H, 15-H or 16-H), 1.2 (d, ^3J = 6.8 Hz, 3H, 15-H or 16-H), 1.95 (m, 1H, 14-H), 3.76 (m, 1H, CpR), 3.86 - 3.90 (m, 1H, CpR), 4.0 - 4.2 (m, 3 x 1H, CpR), 4.02 (s, 5H, CpH), 4.03 (s, 5H, CpH), 4.1 - 4.2 (m, ABX line system, 2H, 12-H or 13-H), 4.24 (m, 1H, CpR), 4.39 (m, ABX line system, 1H, 12-H or 13-H), 4.75 (m, 1H, CpH), 7.1 - 7.41 (m, 5H, Ph), 9.6 (s, 1H, OH) ppm. - ^{13}C NMR (100 MHz, BB, $CDCl_3$): δ = 18.9 (C-15 or C-16), 19.0 (C-15 or C-16), 32.9 (C-14), 64.6 [*C*R-CpR(C-18)], 65.5 (*C*H-CpR), 67.3 (*C*H-CpR), 67.9 (C-12), 68.3 (*C*H-CpR), 68.8 (*C*H-CpH), 68.9 (*C*H-CpR), 70.4 (C-13), 70.7 (*C*H-CpR), 70.8 (*C*H-CpH), 72.1 (*C*H-CpR),

73.9 (*C*H-CpR), 74.5 [*C*R-CpR(C-2)], 98.4 (C-17), 101.7 [*C*R-CpR(C-1)], 126.3 (Ph), 126.5 (Ph), 127.7 (Ph), 148.1 (Ph), 168.2 (C-11) ppm.

5.5.22 (*S,Rp*)-(2-Acetylamino-3-methylbutyl)-2-methylferrocene carboxylate (231)



$C_{19}H_{25}FeNO_3$
Mol. Wt.: 371.3

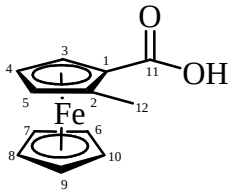
(*S,Rp*)-**231**

To a solution of (*S,Rp*)-2-methylferrocenyl-4-isopropyloxazoline (**122**) (0.591 g, 1.9 mmol) in 20 mL of THF in nitrogen was added H_2O (1.78 mL) and anhydrous Na_2SO_4 (16.700 g). After cooling to 0°C, CF_3COOH (0.78 mL, 10.5 mmol) was added and the reaction stirred at 25 °C for 12 h. An additional 4.800 g of anhydrous Na_2SO_4 was added and the reaction was filtered. The anhydrous Na_2SO_4 was washed with THF until no colour remained and the filtrate was concentrated under reduced pressure affording a black solid. This solid was dissolved in CH_2Cl_2 (33.00 mL), cooled to 0°C and Ac_2O (6.70 mL, 70.8 mmol) was added, followed by pyridine (11.2 mL, 138.6 mmol). The reaction mixture was stirred at 25 °C for 12 h. Hydrolysis was performed by addition of 100 mL of an aqueous 3 M solution of HCl and the layers were separated. The organic phase was washed 3 x 100 mL of H_2O, 100 mL of a saturated aqueous solution of $NaHCO_3$, dried over $MgSO_4$ and the solvent removed at reduced pressure. Column chromatography (SiO_2, 25 x 4 cm, EE) gave pure (*S,Rp*)-(2-acetylamino-3-methylbutyl)-2-methylferrocene carboxylate (**231**) (0.383 g, 1.0 mmol, 54 %) as red-orange liquid.

(*S,Rp*)-231: ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.95 (d, ^3J = 6.8 Hz, 3H, 15-H or 16-H), 0.97 (d, ^3J = 6.8 Hz, 3H, 15-H or 16-H), 1.86 (m, 1H, 14-H), 1.98 (s, 3H, 18-H), 2.22 (s, 3H, 19-H), 4.07 (s, 5H, CpH), 4.20 (m, 1H, CpH), 4.17 - 4.26 (m, 3H, 12-H, 13-H), 4.28 (m 1H, CpH), 4.66 (m, 1H, CpH), 5.93 (d, ^3J = 9.2 Hz, 1H, NH) ppm. - ^{13}C NMR (100 MHz, BB, $CDCl_3$): δ = 14.6 (C-19), 18.4 (C-15 or C-16), 19.2 (C-15 or C-16), 23.3 (C-18), 29.6 (C-14), 53.4 (C-13), 63.9 (C-12), 68.8 (*C*R-CpR), 68.9 (*C*H-CpR), 70.1 (*C*H-CpH), 70.3 (*C*H-CpR),

73.6 (*C*H-CpR), 86.6 (*C*R-CpR),169.9 (C-11), 172.6 (C-17) ppm. - MS (ESI, ES^+): *m / z*: 435 [$M+Na^+$+CH_3CN], 394 [$M+Na^+$]. - HRMS (ESI) ($C_{19}H_{25}FeNNaO_3$): calcd. 394.1082; found 394.1078 [M+Na]. - HRMS (ESI) ($C_{21}H_{28}FeN_2NaO_3$): calcd. 435.1374; found 435.1348 [M+Na+CH_3CN].

5.5.23 (*Rp*)-2-Methylferrocenecarboxylic acid (161)[94]



$C_{12}H_{12}FeO_2$
Mol. Wt.: 244.1

(*Rp*)-**161**

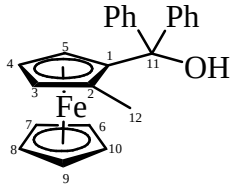
Method A. (*S,Rp*)-(2-Acetylamino-3-methylbutyl)-2-methylferrocene carboxylate (**231**) (0.383 g, 1.0 mmol) was dissolved in 15 mL of THF under nitrogen at 25 °C. Degassed water (15 mL) was added, followed by the addition of degassed aqueous NaOH (5.00 mL, 2.5 M, 12.5 mmol). The resulting deep orange solution was stirred at 50 °C for 16 h and at 70 °C for 4 h. The resulting solution was cooled to 25 °C under nitrogen, extracted with TBME, and the aqueous layer acidified to pH = 4 by slow addition of concentrated HCl. The acidified phase was extracted with CH_2Cl_2 until it became clear, and the combined organic phases were dried over $MgSO_4$. Removal of the solvent at reduced pressure gave (*Rp*)-2 -methylferrocenecarboxylic acid (**161**) (0.187 g, 0.8 mmol, 74 %), identified by comparison with an authentic sample (^{1}H NMR).[94]

Method B. At 0 °C, a solution of (*S,Rp*)-(2-acetylamino-3-methylbutyl) 2-methylferrocene carboxylate (**231**) (0.246 g, 0.7 mmol) in 33 mL of DEE under nitrogen was treated with H_2O (0.06 mL, 3.1 mmol) and *t*-BuOK (1.370 g, 12.2 mmol). The reaction was warmed at 25 °C and stirred for 24h. Hydrolysis was performed by addition of 25 mL of ice water, the layers separated and the aqueous layer washed with 3 x 25 mL of DEE. The aqueous phase was acidified to pH = 4, by slow addition of concentrated HCl, extracted with CH_2Cl_2 until it became clear, dried over $MgSO_4$, and the solvent removed at reduced pressure. Column chromatography (SiO_2, 25 x 4 cm, EE) gave pure (*Rp*)-2 -methylferrocenecarboxylic acid

(**161**) (0.145 g, 0.6 mmol, 90 %), identified by comparison with an authentic sample (^{1}H NMR).[94]

(*Rp*)-161: $[\alpha]^{D}_{20}$ = +44 (*c* = 0.90, EtOH)

5.5.24 (*Rp*)-1-(Diphenylhydroxymethyl)-2-methylferrocene (164)



$C_{24}H_{22}FeO$
Mol. Wt.: 382.3

(*Rp*)-**164**

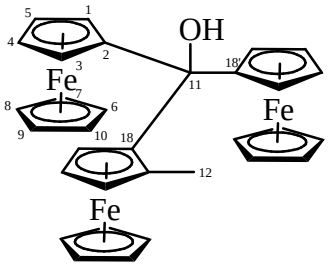
At 25 °C a well stirred solution of (*Rp*)-2-methylferrocenecarboxylic acid (**161**) (0.069 g, 0.28 mmol) in 3 mL of CH_2Cl_2, was treated with oxalyl chloride (0.20 ml, 2.4 mmol) and it was allowed to react for 40 min. The solvent was evaporated at reduced pressure and the red solid was dissolved in 5 mL of anhydrous THF and cooled to –78 °C. Then PhLi (0.5 mL, 1.8 M in cyclohexane, 0.9 mmol) was added and the solution was let to warm to 25 °C. Hydrolysis was performed by addition of 20 mL of H_2O and the organic layer was diluted with 25 mL of TBME and extracted with 3 x 25 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2 deactivated 5% Et_3N in PE, 25 x 2 cm, PE) gave a yellow solid which was recrystallized from PE giving pure (*Rp*)-1-(diphenylhydroxymethyl)-2-methylferrocene (**164**) (0.038 g, 0.1 mmol, 35 %) as yellow crystals (*m.p.* 107 °C).

(*Rp*)-164: $[\alpha]^{D}_{20}$ = +75 (*c* = 0.13, $CHCl_3$). - IR (ATR): $\tilde{\nu}$ = 3514 cm^{-1} (w, -OH), 3078 (w, Cp-H), 2962 (w, CH), 2897 (s, CH), 2863 (s, CH). - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.56 (s, 3H, C-12), 3.48 (m, 1H, CpR), 3.78 (s, 1H, OH), 4.05 (m, 1H, CpR), 4.18 (m, 1H, CpR), 4.20 (s, 5H, CpH), 7.10 - 7.50 (m, 10H, Ph) ppm. - ^{13}C NMR (100 MHz, BB, HMQC, HMBC, $CDCl_3$): δ = 14.6 (C-12), 65.4 (CH-CpR), 69.0 (CH-CpH), 71.5 (CH-CpR), 71.6 (CH-CpR), 77.3 (C-11), 82.7 [*C*R-CpR(C-2)], 99.3 [*C*R-CpR(C-1)], 126.5 (Ph), 126.6 (Ph), 126.8 (Ph), 127.22 (Ph), 127.24 (Ph), 127.6 (Ph) 145.8 (Ph), 146.7 (Ph) ppm. - MS (ESI, ES^+): *m / z*: 365

[M^+–OH], 382 [M^+]. - HRMS (ESI) ($C_{24}H_{22}OFe$): calcd. 382.1020; found 382.1014 [M]. - HRMS (ESI) ($C_{24}H_{21}Fe$): calcd. 365.0993; found 365.0994 [M–OH]. - $C_{24}H_{22}FeO$: calcd. C 75.41, H 5.80; found C 75.08, H 5.63.

Crystal Structure Analysis of (*Rp*)-**164:** $C_{24}H_{22}FeO$, molecular weight, 764.53 g / mol, temperature 298(2) K, Wavelength 0.71073 Å, crystal system monoclinic, space group P2, (No 1), a = 7.390(2), b = 14.729(3), c = 9.332(3) Å, α = 90°, β = 112.56(3)°, γ = 90°, V = 937.9(4) $Å^3$, Z = 2, $\rho_{calcd.}$ = 1.354 mg m^{-3}, F(000) = 400, Absorption coefficient = 0.813 mm^{-1}, Crystal size 0.30 x 0.24 x 0.12 mm, Stoe IPDS area detector diffractometer, θ-range = 2.36 to 26.16°, Limiting indices –9<=h<=9, –18<=k<=18, –11<=l<=11, Reflections collected / unique 13325 / 3601 [R(int) = 0.0918], completeness of data (θ = 26.16): 95.8%, no absorption correction, no extinction correction, refinement method: Full-matrix least-squares on F^2, goodness-of-fit on F^2 = 0.542, R-indices[I>2σ(I)]: R_1 = 0.0311, wR_2 = 0.0564, R-indices [all data]: R_1 = 0.0978, wR_2 = 0.0751, minimal and maximal residual electron density – 0.222 / 0.145 e$Å^{-3}$.

5.5.25 (*Rp*)-1-(Diferroceylhydroxymethyl)-2-methylferrocene (165)



$C_{32}H_{30}Fe_3O$
Mol. Wt.: 598.1

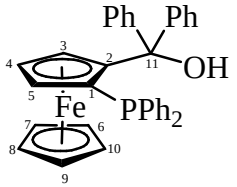
(*Rp*)-**165**

At 25 °C a well stirred solution of (*Rp*)-2-methylferrocenecarboxylic acid (**161**) (0.102 g, 0.4 mmol) in 1.5 mL of CH_2Cl_2 was treated with oxalyl chloride (0.07 ml, 0.8 mmol) and it was allowed to react for 40 min. The solvent was evaporated at reduced pressure and the red solid was dissolved in 10 mL of anhydrous THF and cooled to –78 °C. Then lithiumferrocene [from Fc (0.500 g, 2.7 mmol); THF / hexane 1:1 (2.50 mL); *t*-BuLi (1.5 mL, 1.7 M, 2.5 mmol)] was added and the solution was allowed to warm to 25 °C. Hydrolysis was performed

by addition of 20 mL of H_2O and the organic layer was diluted with 25 mL of TBME and extracted with 3 x 25 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2 deactivated 5% Et_3N in PE, 25 x 2 cm, PE / CH_2Cl_2 7:3) gave pure (*Rp*)-1-(diferrocenylhydroxymethyl)-2-methylferrocene (**165**) (0.078 g, 0.1 mmol, 31 %) as an orange-yellow solid (*m.p.* 193°C).

(*Rp*)-165: $[\alpha]^{D}_{20}$ = +220 (*c* = 0.16, $CHCl_3$). - IR (ATR): $\tilde{\nu}$ = 3542 cm^{-1} (w, -OH), 3088 (w, Cp-H), 2943 (w, CH), 2898 (s, CH), 2861 (s, CH). - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.40 (s, 3H, 12-H), 3.05 (s, 1H, OH), 3.55 (m, 1H, CpR), 3.63 (m, 1H, CpR), 3.99 (m, 1H, CpR), 4.05 (m, 2H, CpR), 4.07 (m, 1H, CpR), 4.13 (m, 5H, CpH), 4.17 (m, 5H, CpH), 4.20 (m, 1H, CpR), 4.22 (m, 5H, CpH), 4.26 (m, 1H, CpR), 4.32 (m, 1H, CpR), 4.46 (m, 1H, CpR), 4.65 (m, 1H, CpR) ppm. - ^{13}C NMR (100 MHz, BB, HMQC, HMBC, $CDCl_3$): δ = 14.9 (C-12), 64.2 (*C*H-CpR), 66.3 (*C*H-CpR), 66.4 (*C*H-CpR), 66.6 (*C*H-CpR), 66.8 (*C*H-CpR), 66.9 (*C*H-CpR), 67.46 (*C*H-CpR), 67.5 (*C*H-CpR), 68.7 (*C*H-CpH), 68.78 (*C*H-CpH), 68.8 (*C*H-CpR), 69.4 (*C*H-CpH), 70.5 (*C*H-CpR), 71.54 (*C*H-CpR), 71.57 (C-11), 81.7 (*C*R-CpR), 96.7 (*C*R-CpR), 99.86 (*C*R-CpR), 100.4 (*C*R-CpR) ppm. - MS (ESI, ES^+): *m / z*: 598 [M^+], 581[M^+–OH], 566 [M^+–OH–CH_3]. - HRMS (ESI) ($C_{32}H_{30}Fe_3O$): calcd. 598.0345; found 598.0325 [M].

5.5.26 (*Sp*)-2-(Diphenylhydroxymethyl)-1-diphenylphosphinoferrocene (163)



$C_{35}H_{29}FeOP$
Mol. Wt.: 552.4

(*Sp*)-**163**

At 25 °C a well stirred solution of (*Rp*)-2-diphenylphosphinoferrocenecarboxylic acid (**162**) (0.098 g, 0.2 mmol) in 15 mL of CH_2Cl_2 was treated with oxalyl chloride (0.05 ml, 0.5 mmol) and it was allowed to react for 30 min. The solution was evaporated at reduced pressure and the red solid was dissolved in 30 mL of anhydrous THF and cooled to -78 °C. Then PhLi (0.30 mL, 1.8 M in cyclohexane, 0.5 mmol) was added and the reaction mixture allowed to

warm to 25 °C. Hydrolysis was performed by addition of 20 mL of H_2O, the organic layer diluted with 25 mL of TBME, extracted with 3 x 25 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2, 25 x 2 cm, PE / CH_2Cl_2 1:1) gave pure (*Sp*)-2-(diphenylhydroxymethyl)-1-diphenylphosphinoferrocene (**163**) (0.058 g, 0.1 mmol, 50 %) as a yellow solid (*m.p.* 199 °C).

(*Sp*)-163: $[\alpha]^{D}_{20}$ = –63(*c* = 0.68, $CHCl_3$). - IR (ATR): $\tilde{\nu}$ = 3300 cm^{-1} (w, -OH), 3084 (w, Cp-H), 3057 (w, Cp-H), 2960 (w, CH), 2924 (s, CH), 2854 (s, CH). - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 3.93 (m, 1H, CpR), 4.24 (s, 5H, CpH), 4.28 (m, 1H, CpR), 4.39 (m, 1H, CpR), 6.70 (m, 3H, Ph), 7.06 (m, 2H, Ph), 7.21 (m, 3H, Ph), 7.32 (m, 5H, Ph), 7.54 (m, 5H, Ph), 7.9 (m, 2H, Ph), 8.0 (s, 1H, OH) ppm. - ^{13}C NMR (100 MHz, BB, APT, HMQC, HMBC, 297 K, $CDCl_3$): δ = 67.9 [+, *J* = 112.0 Hz, *C*R-CpR(C-1)], 69.3 (–, *J* = 11.4 Hz, *C*H-CpR), 70.6 (–, *C*H-CpH), 73.3 (–, *J* = 15.0 Hz, *C*H-CpR), 76.10 (–, *J* = 9.3 Hz, *C*H-CpR), 76.7 (+, C-11), 105.9 (+, *J* = 10.3 Hz, *C*R-CpR), 126.2 (–, Ph), 126.4 (–, Ph), 126.6 (–, Ph), 127.1 (–, Ph), 127.4 (–, Ph), 127.5 (–, Ph), 127.8 (–, *J* = 12.4 Hz, Ph), 128.2 (–, *J* = 12.0 Hz, Ph), 130.4 (–, *J* = 9.7 Hz, Ph), 130.7 (–, *J* = 2.9 Hz, Ph), 131.3 (–, *J* = 9.5 Hz, Ph), 131.6 (–, *J* = 2.7 Hz, Ph), 132.4 (+, ^{1}*J* = 25.3 Hz, Ph), 133.5 (+, ^{1}*J* = 25.7 Hz, Ph), 145.5 (+, Ph), 147.1 (+, Ph) ppm. - ^{31}P NMR (121.5 MHz, $CDCl_3$): δ = 31.4 (PPh_2) ppm. - MS (ESI, ES^+): *m / z*: 591 [$M+K^+$], 551 [M^++O–OH]. - HRMS (ESI) ($C_{35}H_{28}FeOP$): calcd. 551.1227; found: 551.1237 [M+H].

5.6 Asymmetric Additions to Aldehydes

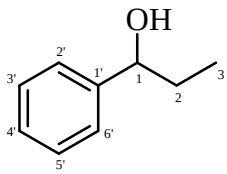
5.6.1 General Procedure for the Preparation of the Racemic Arylic Alcohols

All the racemic alcohols used for the GC or ^{1}H NMR analysis were prepared according to the following procedure unless otherwise indicated. Under nitrogen a 5 mL of a 1.0 M solution of EtMgBr [from Mg (2.000 g, 83.0 mmol), ethyl bromide (6.0 mL, 80.0 mmol) in 80 mL of anhydrous Et_2O] was added into a solution of an aldehyde (0.05 mmol) in 10 mL of anhydrous THF. After the mixture was stirred for 1 h, hydrolysis was performed by addition of ice water, and the reaction mixture was extracted with DEE, dried over $MgSO_4$, and the solvent was removed at reduced pressure. The residue was passed through a short silica gel column to afford the desired products.

5.6.2 General Procedure for the Catalytic Asymmetric Addition of Diethylzinc to Aldehydes (GP3)

To a solution of ferrocene ligand (0.03 mmol) in 1.25 mL of anhydrous toluene, diethylzinc (1.00 ml, 1.0 mmol, 1.0 M in hexane) was added at room temperature. After 30 min, the reaction system was cooled to 0°C, and the aldehyde (0.5 mmol) was added in an argon atmosphere. After having them stirred for the appropriate time, the reaction was quenched by addition of 5 mL of 3.0 M HCl aqueous solution. The mixture was extracted with 3 x 5 mL of TBME. The organic layer was washed with 2 x 25 mL of brine, dried over $MgSO_4$, and the solvent was evaporated at reduced pressure to give an oily residue. Purification by column chromatography (SiO_2, 25 x 2 cm) gave the optically active alcohol. The enantiomeric excess was determined by GC analysis or by ^1H NMR. Configurations were assigned by comparison with the sign of specific rotation of the known compound.

5.6.3 (*R*)-1-Phenyl-propan-1-ol (232)[79]



$C_9H_{12}O$
Mol. Wt.: 136.2

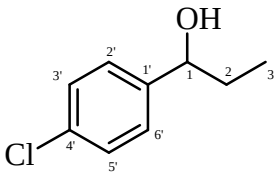
(*R*)-**232**

GP3: (*S*,*Rp*)-2-(2-Diphenylhydroxymethylferrocenyl)-4-isopropyloxazoline (**128**) (0.012 g, 0.03 mmol); diethylzinc (1.00 mL, 1.0 M in hexane, 1.0 mmol); toluene (1.25 mL); benzaldehyde (0.05 mL, 0.5 mmol); 25 °C; 24 h; column chromatography (SiO_2, 25 x 2 cm, PE / EE 10:1) gave (*R*)-1-phenyl-propan-1-ol (**232**) (0.065 g, 0.5 mmol, 97 %, 83 % *ee*).

GP3: (*S*,*Rp*)-2-(2-Diferrocenylhydroxymethylferrocenyl)-4-isopropyloxazoline (**129**) (0.017 g, 0.03 mmol); diethylzinc (1.00 mL, 1.0 M in hexane, 1.0 mmol); toluene (1.25 mL); benzaldehyde (0.05 mL, 0.5 mmol); 25°C; 24 h; column chromatography (SiO_2, 25 x 2 cm, PE / EE 10:1) gave (*R*)-1-phenyl-propan-1-ol (**232**) (0.063 g, 0.5 mmol, 95 %, 97 % *ee*).

(*R*)-232: ^{1}H NMR (200 MHz, $CDCl_3$): δ = 0.91 (t, *J* = 7.4 Hz, 3H, 3-H), 1.77 (m, 2H, 2-H), 2.2 (br, 1H, O*H*), 4.58 (t, *J* = 6.6 Hz, 1H, 1-H), 7.3 (m, 5H, Ph) ppm. - GC (95 °C isobar 60 min - 1 °C / min - 170 °C) R_t = 76.615 min (*R*), 84.713 min (*S*).

5.6.4 (*R*)-1-(4-Chlorophenyl)-propan-1-ol (233)[79]



$C_9H_{11}ClO$
Mol. Wt.: 170.6

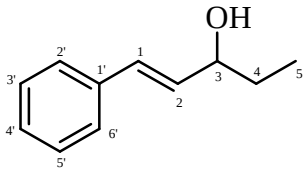
(*R*)-**233**

GP3: (*S*,*Rp*)-2-(2-Diphenylhydroxymethylferrocenyl)-4-isopropyloxazoline (**128**) (0.012 g, 0.03 mmol); diethylzinc (1.00 mL, 1.0 M in hexane, 1.0 mmol); toluene (1.25 mL); 4-chlorobenzaldehyde (0.072 g, 0.5 mmol); 25 °C; 24 h; column chromatography (SiO_2, 25 x 2 cm, PE / EE 10:1); gave (*R*)-1-(4-chlorophenyl)-propan-1-ol (**233**) (0.070 g, 0.4 mmol, 80 %, 85 % *ee*).

GP3: (*S*,*Rp*)-2-(2-Diferrocenylhydroxymethylferrocenyl)-4-isopropyloxazoline (**129**) (0.017 g, 0.03 mmol); diethylzinc (1.00 mL, 1.0 M in hexane, 1.0 mmol); toluene (1.25 mL); 4-chlorobenzaldehyde (0.072 g, 0.5 mmol); 25 °C; 24 h; column chromatography (SiO_2, 25 x 2 cm, PE / EE 10:1) gave (*R*)-1-(4-chloro-phenyl)-propan-1-ol (**233**) (0.068 g, 0.4 mmol, 80 %, 97.2 % *ee*).

(*R*)-233: ^{1}H NMR (200 MHz, $CDCl_3$): δ = 0.93 (t, ^3J = 7.4 Hz, 3H, 3-H), 1.69 - 1.86 (m, 2H, 2-H), 2.16 (s, 1H, O*H*), 4.60 (t, ^3J = 6.5 Hz, 1H, 1-H), 7.30 (AA'BB' line system, 4H, Ph) ppm. - GC (70 °C - 0.5 °C / min - 210 °C) R_t = 125.078 min (*R*), 129.658 min (*S*).

5.6.5 (*R*)-1-Phenylpent-1-en-3-ol (234)[79]



$C_{11}H_{14}O$
Exact Mass: 162.1

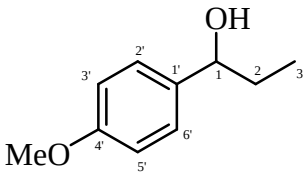
(*R*)-**234**

GP3: (*S*,*Rp*)-2-(2-Diphenylhydroxymethylferrocenyl)-4-isopropyloxazoline (**128**) (0.012 g, 0.03 mmol); diethylzinc (1.00 mL, 1.0 M in hexane, 1.0 mmol); toluene (1.25 mL); 3-phenylpropenal (0.06 mL, 0.5 mmol); 25 °C; 24 h; column chromatography (SiO_2, 25 x 2 cm, PE / EE 10:1) gave (*R*)-1-phenylpent-1-en-3-ol (**234**) (0.061 g, 0.4 mmol, 92 %, 70% *ee*).

GP3: (*S*,*Rp*)-2-(2-Diferrocenylhydroxymethylferrocenyl)-4-isopropyloxazoline (**129**) (0.017 g, 0.03 mmol); diethylzinc (1.00 mL, 1.0 M in hexane, 1.0 mmol); toluene (1.25 mL), 3-phenylpropenal (0.06 ml, 0.5 mmol); 25 °C; 24 h; column chromatography (SiO_2, 25 x 2 cm, PE / EE 10:1) gave (*R*)-1-phenylpent-1-en-3-ol (**234**) (0.081 g, 0.5 mmol, 99 %, 80 % *ee*).

(*R*)-234: ^{1}H NMR (200 MHz, $CDCl_3$): δ = 0.95 (t, ^3J = 7.46 Hz, 3H, 5-H), 1.60 - 1.69 (m, 2H, 4-H), 2.0 (s, 1H, OH), 4.19 (dd, ABX line system, ^3J = ^3J = 6.4 Hz, 1H, 3-H), 6.19 (dd, ^3J = 6.64 Hz, ^3J = 16 Hz, 1H, 2-H), 6.55 (d, ^3J = 16 Hz, 1H, 1-H), 7.22 - 7.3 (m, 5H, Ph) ppm.

5.6.6 (*R*)-1-(4-Methoxyphenyl)propan-1-ol (235)[79]



$C_{10}H_{14}O_2$
Mol. Wt.: 166.2

(*R*)-**235**

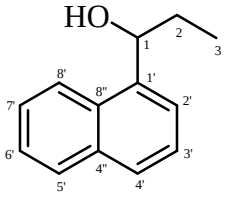
GP3: (*S*,*Rp*)-2-(2-Diphenylhydroxymethylferrocenyl)-4-isopropyloxazoline (**128**) (0.012 g, 0.03 mmol); diethylzinc (1.00 mL, 1.0 M in hexane, 1.0 mmol); toluene (1.25 mL); 4-methoxybenzaldehyde (0.07 mL, 0.6 mmol); 25 °C; 24 h; column chromatography (SiO_2, 25

x 2 cm, PE / EE 10:1) gave (*R*)-1-(4-methoxyphenyl)propan-1-ol (**235**) (0.095 g, 0.6 mmol, 99 %, 84 % *ee*).

GP3: (*S*,*Rp*)-2-(2-Diferrocenylhydroxymethylferrocenyl)-4-isopropyloxazoline (**129**) (0.017 g, 0.03 mmol); diethylzinc (1.00 mL, 1.0 M in hexane, 1.0 mmol); toluene (1.25 mL); 4-methoxybenzaldehyde (0.07 ml, 0.6 mmol); 25 °C; 24 h; column chromatography (SiO_2, 25 x 2 cm, PE / EE 10:1) gave (*R*)-1-(4-methoxyphenyl)propan-1-ol (**235**) (0.091 g, 0.5 mmol, 95 %, 90 % *ee*).

(*R*)-235: ^{1}H NMR (200 MHz, $CDCl_3$): δ = 0.9 (t, ^3J = 7.4 Hz, 3H, 3-H), 1.8 (m, 2H, 2-H), 2.7 (br, 1H, OH), 3.8 (s, 3H, MeO), 4.9 (m, 1H, 1-H), 6.8 - 6.9 + 7.2 - 7.3 [AA´BB´ line system, 4H, 3´-(2', 5´, 6')H] ppm. - GC (70 °C - 1 °C / min - 210 °C) R_t = 71.7 min (*S*), 73.9 min (*R*).

5.6.7 (*R*)-1-Naphthalen-1-ylpropan-1-ol (236)[79]



$C_{13}H_{14}O$
Mol. Wt.: 186.2

(*R*)-**236**

GP3: (*S*,*Rp*)-2-(2-Diphenylhydroxymethylferrocenyl)-4-isopropyloxazoline (**128**) (0.012 g, 0.03 mmol); diethylzinc (1.00 mL, 1.0 M in hexane, 1.0 mmol); toluene (1.25 mL); naphthalene-1-carbaldehyde (0.07 mL, 0.5 mmol); 25 °C; 24 h; column chromatography (SiO_2, 25 x 2 cm, PE / EE 10:1) gave (*R*)-1-naphthalen-1-ylpropan-1-ol (**236**) (0.090 g, 0.5 mmol, 94 %, 90 % *ee*).

GP3: (*S*,*Rp*)-2-(2-Diferrocenylhydroxymethylferrocenyl)-4-isopropyloxazoline (**129**) (0.017 g, 0.03 mmol); diethylzinc (1.00 mL, 1.0 M in hexane, 1.0 mmol); toluene (1.25 mL); naphthalene-1-carbaldehyde (0.07 ml, 0.5 mmol); 25 °C; 24 h; column chromatography (SiO_2, 25 x 2 cm, PE / EE 10:1) gave (*R*)-1-naphthalen-1-ylpropan-1-ol (**236**) (0.094 g, 0.5 mmol, 98 %, 97 % *ee*).

(*R*)-236: ^{1}H NMR (200 MHz, $CDCl_3$): δ = 1.03 (t, ^{3}J = 7.4 Hz, 3H, 3-H), 1.76 - 2.06 (m, 2H, 2-H), 2.3 (br, 1H, OH), 5.37 (dd, ^{3}J = 5.3 Hz, ^{3}J = 7.14 Hz, 1H, 1-H), 7.43 - 7.55 (m, 4H, Ph), 7.6 - 8.5 (m, 3H, Ph) ppm. - GC (70 °C - 2.5 °C / min - 210 °C) R_t = 75.28 min (*S*), 76.722 min (*R*).

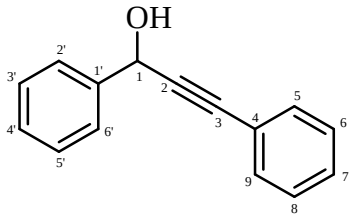
5.6.8 General Procedure for the Preparation of the Racemic Propargylic Alcohols

All the racemic alcohols used for the HPLC analysis were prepared according to the following procedure unless otherwise indicated. Under nitrogen, BuLi (5 mL, 1.6 M, mmol) was added into a solution of an alkyne (0.05 mmol) in 10 mL of anhydrous THF. After the mixture was stirred for 1h, hydrolysis was performed by addition of ice water, and the reaction mixture was extracted with DEE, dried over $MgSO_4$ and the solvent was removed at reduced pressure. The residue was filtered through a short silica gel column to afford the desired products.

5.6.9 General Procedure for the Catalytic Asymmetric Addition of Alkynylzinc to Aldehydes (GP4)

At 25 °C, phenylacetylene was added to a solution of Et_2Zn in anhydrous CH_2Cl_2 in an argon atmosphere. The resulting mixture was stirred 2h at 25 °C after which the ferrocene ligand was added and the reaction mixture stirred for additional 30 min. The reaction system was cooled to 0°C at which point the aldehyde was added under an argon atmosphere. After having been stirred the appropriate time, the reaction was quenched by addition of a saturated aqueous solution of NH_4Cl. The mixture was extracted with TBME, the organic layer washed with 2 x 25 mL of brine, dried over $MgSO_4$, and the solvent was removed at reduced pressure to give an oily residue. Purification of the residue by column chromatography gave the optically active alcohol.

5.6.10 1,3-Diphenylprop-2-yn-1-ol (237)[90]



$C_{15}H_{12}O$
Mol. Wt.: 208.3

237

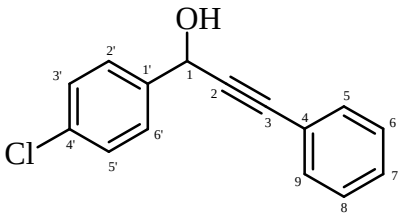
GP4: (*S*,*Rp*)-2-(2-Diphenylhydroxymethylferrocenyl)-4-isopropyloxazoline (**128**) (0.012 g, 0.03 mmol); diethylzinc (0.6 mL, 1.0 M in hexane, 0.6 mmol); phenylacetylene (0.065 mL, 0.6 mmol); CH_2Cl_2 (2.0 mL); benzaldehyde (0.05 mL, 0.5 mmol); 25 °C; 24 h; column chromatography (SiO_2, 25 x 2 cm, PE / EE 10:1 then EE) gave of 1,3-diphenylprop-2-yn-1-ol (**237**) (0.077 g, 0.4 mmol, 75 %, 5.4 % *ee*).

GP4: (*S*,*Rp*)-2-(2-Diphenylhydroxymethylferrocenyl)-4-isopropyloxazoline (**128**) (0.012 g, 0.03 mmol); diethylzinc (1.2 mL, 1.0 M in hexane, 1.2 mmol); phenylacetylene (0.14 mL, 1.3 mmol); CH_2Cl_2 (2.0 mL); benzaldehyde (0.2 mL, 1.9 mmol); 25 °C; 24 h; column chromatography (SiO_2, 25 x 2 cm, PE / EE 10:1 then EE) gave 0.130 g of a 4:1 mixture of 1,3-diphenylprop-2-yn-1-ol (**237**) (0.120 g, 0.5 mmol, 42 %, 1.3 % *ee*) and 1-phenylpropan-1-ol (**232**) (0.010g, 0.1 mmol, 8 %).

GP4: (*S*,*Rp*)-2-(2-Diferrocenylhydroxymethylferrocenyl)-4-isopropyloxazoline (**129**) (0.017 g, 0.03 mmol); diethylzinc (1.2 mL, 1.0 M in hexane, 1.2 mmol); phenylacetylene (0.14 mL, 1.3 mmol); CH_2Cl_2 (2.0 mL); benzaldehyde (0.2 mL, 1.9 mmol); 25 °C; 24 h; column chromatography (SiO_2, 25 x 2 cm, PE / EE 10:1 then EE) gave 0.176 g of a 4:1 mixture of 1,3-diphenylprop-2-yn-1-ol (**237**) (0.151 g, 0.7 mmol, 58 %, 1.22 % *ee*) and 1-phenylpropan-1-ol (**232**) (0.025 g, 0.2 mmol, 17 %).

237: ^{1}H NMR (200 MHz, $CDCl_3$): δ = 2.80 (d, ^3J = 5.8 Hz, 1H, O*H*), 5.64 (d, ^3J = 5.6 Hz, 1H, 1-H), 7.26 - 7.70 (m, 10H, Ph) ppm. - ^{13}C NMR (50 MHz, APT, $CDCl_3$): δ = 64.9 (–, C-1), 86.5 (+, C-3), 88.8 (+, C-2), 122.4 (+, C-4), 125.9 (–, Ph), 126.7 (–, Ph), 128.2 (–, Ph), 128.3 (–, Ph), 128.5 (–, Ph), 131.7 (–, Ph), 140.6 (+, C-1') ppm.

5.6.11 1-(4-Chlorophenyl)-3-phenylprop-2-yn-1-ol (238)[90]



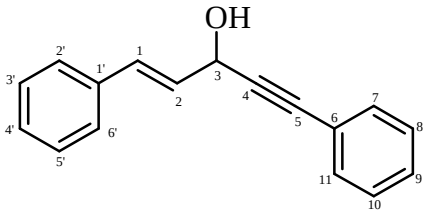
238

$C_{15}H_{11}ClO$
Mol. Wt.: 242.7

GP4: (*S,Rp*)-2-(2-Diphenylhydroxymethylferrocenyl)-4-isopropyloxazoline (**128**) (0.012 g, 0.03 mmol); diethylzinc (1.2 mL, 1.0 M in hexane, 1.2 mmol); phenylacetylene (0.14 mL, 1.3 mmol); CH_2Cl_2 (2.0 mL); 4-chlorobenzaldehyde (0.072 g, 0.5 mmol); 25 °C; 24 h; column chromatography (SiO_2, 25 x 2 cm, PE / EE 10:1 then EE) gave 0.082 g of a 1:1 mixture of 1-(4-chlorophenyl)-3-phenylprop-2-yn-1-ol (**238**) (0.048 g, 0.2 mmol, 40 %, 18.7 % *ee*) and 1-(4-chlorophenyl)propan-1-ol (**233**) (0.034 g, 0.2 mmol, 40 %).

238: ^{1}H NMR (200 MHz, $CDCl_3$): δ = 2.87 (br, 1H, O*H*), 5.69 (br, 1H, 1-H), 7.26 - 7.70 (m, 9H, Ph) ppm.

5.6.12 1,5-Diphenylpent-1-en-4-yn-3-ol (239)[90]



239

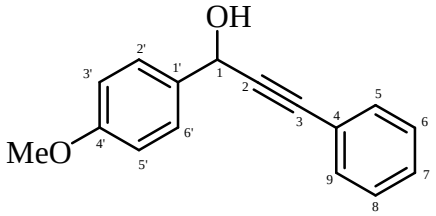
$C_{17}H_{14}O$
Mol. Wt.: 234.3

GP4: (*S,Rp*)-2-(2-Diphenylhydroxymethylferrocenyl)-4-isopropyloxazoline (**128**) (0.012 g, 0.03 mmol); diethylzinc (1.2 mL, 1.0 M in hexane, 1.2 mmol); phenylacetylene (0.14 mL, 1.3 mmol); CH_2Cl_2 (2.0 mL); 3-phenylpropenal (0.03 g, 2.4 mmol); 25 °C; 24 h; column chromatography (SiO_2, 25 x 2 cm, PE / EE 10:1 then EE) gave 0.245 g of a 1:2 mixture of 1,5-diphenylpent-1-en-4-yn-3-ol (**239**) (0.103 g, 0.4 mmol, 33 %, 6.4 % *ee*) and 1-phenylpent-1-en-3-ol (**234**) (0.142 g, 0.8 mmol, 75 %).

GP4: (*S,Rp*)-2-(2-Diferrocenylhydroxymethylferrocenyl)-4-isopropyloxazoline (**129**) (0.017 g, 0.03 mmol); diethylzinc (1.2 mL, 1.0 M in hexane, 1.2 mmol); phenylacetylene (0.14 mL, 1.3 mmol); CH_2Cl_2 (2.0 mL); 3-phenylpropenal (0.03 g, 2.4 mmol); 25 °C; 24 h; column chromatography (SiO_2, 25 x 2 cm, PE / EE 10:1 then EE) gave 0.245 g of a 2:1 mixture of 1,5-diphenylpent-1-en-4-yn-3-ol (**239**) (0.182 g, 0.8 mmol, 65 %, 14.6 % *ee*) and 1-phenylpent-1-en-3-ol (**234**) (0.063 g, 0.4 mmol, 32 %).

239: ^{1}H NMR (200 MHz, $CDCl_3$): δ = 2.35 (br, 1H, O*H*), 5.35 (d, ^3J = 5.4 Hz, 1H, 1-H), 6.46 (dd, ^3J = 5.9 Hz, ^3J = 15.7 Hz, 1H, 2-H), 6.69 (dd, ^4J = 0.9 Hz, ^3J = 15.8 Hz, 1H, 1-H), 7.26 - 7.70 (m, 10H, Ph) ppm.

5.6.13 1-(4-methoxyphenyl)-3-phenylprop-2-yn-1-ol (240)[90]



$C_{16}H_{14}O_2$
Mol. Wt.: 238.3

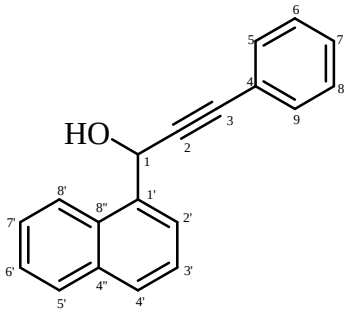
240

GP4: (*S,Rp*)-2-(2-Diphenylhydroxymethylferrocenyl)-4-isopropyloxazoline (**128**) (0.012 g, 0.03 mmol); diethylzinc (1.2 mL, 1.0 M in hexane, 1.2 mmol); phenylacetylene (0.14 mL, 1.3 mmol); CH_2Cl_2 (2.0 mL); 4-methoxybenzaldehyde (0.3 mL, 2.5 mmol); 25 °C; 24 h; column chromatography (SiO_2, 25 x 2 cm, PE / EE 10:1 then EE) gave 1-(4-methoxyphenyl)-3-phenylprop-2-yn-1-ol (**240**) (0.218 g, 0.9 mmol, 76 %, 16.5 % *ee*).

GP4: (*S,Rp*)-2-(2-Diferrocenylhydroxymethylferrocenyl)-4-isopropyloxazoline (**129**) (0.017 g, 0.03 mmol); diethylzinc (1.2 mL, 1.0 M in hexane, 1.2 mmol); phenylacetylene (0.14 mL, 1.3 mmol); CH_2Cl_2 (2.0 mL); 4-methoxybenzaldehyde (0.2 mL, 1.9 mmol); 25 °C; 24 h; column chromatography (SiO_2, 25 x 2 cm, PE / EE 10:1 then EE) gave 1-(4-methoxyphenyl)-3-phenylprop-2-yn-1-ol (**240**) (0.158 g, 0.7 mmol, 55 %, 18.6 % *ee*).

240: ^{1}H NMR (200 MHz, $CDCl_3$): δ = 3.3 (br, 1H, OH), 3.84 (s, 3H, OMe), 5.92 (br, 1H, 1-H), 6.85 - 7.00 (m, 2H, Ph), 7.34 - 7.42 (m, 4H), 7.52 - 7.54 (m, 2H), 7.7 (m, 1H) ppm.

5.6.14 1-naphthalen-1-yl-3-phenylprop-2-yn-1-ol (241)[90]



$C_{19}H_{14}O$
Mol. Wt.: 258.3

241

GP4: Diethylzinc (1.2 mL, 1.0 M in hexane, 1.2 mmol); phenylacetylene (0.14 mL, 1.3 mmol); CH_2Cl_2 (2.0 mL); naphthalene-1-carbaldehyde (0.3 mL, 2.2 mmol); 25 °C; 24 h; column chromatography (SiO_2, 25 x 2 cm, PE / EE 10:1 then EE) gave naphthalene-1-carbaldehyde (**241**) (0.330 g, 2.1 mmol, 95 %).

GP4: (*S,Rp*)-2-(2-Diphenylhydroxymethylferrocenyl)-4-isopropyloxazoline (**128**) (0.012 g, 0.03 mmol); diethylzinc (1.2 mL, 1.1 M in hexane, 1.3 mmol); phenylacetylene (0.14 mL, 1.3 mmol); CH_2Cl_2 (2.0 mL); naphthalene-1-carbaldehyde (0.3 mL, 2.2 mmol); 25 °C; 24 h; column chromatography (SiO_2, 25 x 2 cm, PE / EE 10:1 then EE) gave 0.345 g of a 7:1 mixture of 1-naphthalen-1-yl-3-phenylprop-2-yn-1-ol (**241**) (0.312 g, 1.2 mmol, 92 %) and 1-naphthalen-1-yl-propan-1-ol (**236**) (0.032 g, 0.2 mmol, 15 %).

GP4: (*S,Rp*)-2-(2-Diferrocenylhydroxymethylferrocenyl)-4-isopropyloxazoline (**129**) (0.017 g, 0.03 mmol); diethylzinc (1.2 mL, 1.1 M in hexane, 1.3 mmol); phenylacetylene (0.14 mL, 1.3 mmol); CH_2Cl_2 (2.0 mL); naphthalene-1-carbaldehyde (0.3 mL, 2.2 mmol); 25 °C; 24 h; column chromatography (SiO_2, 25 x 2 cm, PE / EE 10:1 then EE) gave 0.283 g of a 4:1 mixture of 1-naphthalen-1-yl-3-phenylprop-2-yn-1-ol (**241**) (0.240 g, 0.9 mmol, 70 %) and 1-naphthalen-1-ylpropan-1-ol (**236**) (0.043 g, 0.2 mmol, 15 %).

241: ^{1}H NMR (200 MHz, $CDCl_3$): δ = 3.27 (br, 1H, OH), 6.35 (s, 1H, 1-H), 7.32 - 7.45 (m, 3H, Ph), 7.50 - 7.70 (m, 5H), 7.80 - 8.00 (m, 3H), 8.30 - 8.50 (m, 1H) ppm.

5.7 Suzuki-Miyaura Coupling Reactions

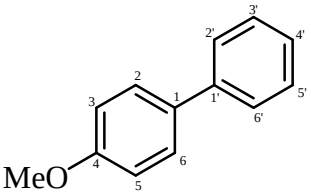
5.7.1 General Procedure for the Synthesis of Biaryls (GP5)

The palladium source (0.02 mmol), the boronic acid (1.5 mmol) and KF (3.0 mmol) were added in a Schlenk tube under argon. The Schlenk tube was evacuated and then refilled with argon three times. Next the solution of the phosphine (0.01 M in THF, 0.02 mmol) was added, the Schlenk tube sealed, and the reaction stirred at the indicate temperature for the indicate amount of time. Hydrolysis was performed by addition of H_2O and the reaction mixture was diluted with EE. The organic layer was washed with 3 x 25 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography gave pure biaryl.

5.7.2 General Procedure for the Synthesis of Biaryls Assisted by Microwave Irradiation (GP6)

The palladium source (0.02 mmol), the boronic acid (1.5 mmol) and KF (3.0 mmol) were added in a heavy-walled vial under argon. The vial was evacuated and then refilled with argon three times. Next the solution of phosphine (0.01 M in THF, 0.02 mmol) was added, the vial sealed, and the contents of the flask were irradiated for 1 h with a power of 250 W heating until a maximum of 150 °C. Hydrolysis was performed by addition of H_2O and the reaction mixture was diluted with EE. The organic layer was washed with 3 x 25 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography gave pure biaryl.

5.7.3 4-Methoxybiphenyl (242)[44]



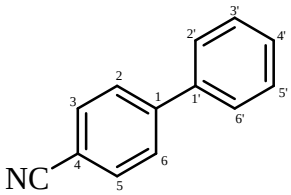
$C_{13}H_{12}O$
Mol. Wt.: 184.2

242

GP6: $Pd(dba)_2$ (0.006 g, 0.02 mmol); phenylboronic acid (0.183 g, 1.5 mmol); KF (0.174 g, 3.0 mmol); diphenyl(2,2,2-triferrocenylethyl)phosphine (**58**) (2 mL, 0.01 M in THF, 0.02 mmol); 1-bromo-4-methoxybenzene (0.12 mL, 0.9 mmol); column chromatography (SiO_2, 25 x 2 cm, PE / EE 15:1) gave pure 4-methoxybiphenyl (**242**) (0.155 g, 0.8 mmol, 89 %).

242: ^{1}H NMR (200 MHz, $CDCl_3$): δ = 3.7 (s, 3H, CH_3), 6.91 - 6.95 (m, 2H, Ph), 7.25 - 7.50 (m, 7H, Ph) ppm. - ^{13}C NMR (50 MHz, APT, $CDCl_3$): δ = 55.2 (–, MeO), 114.2 (–), 126.6 (–), 126.7 (–), 128.0 (–), 128.7 (–), 133.7 (+, C-1), 140.8 (+, C-1'), 159.1 (+, C-4) ppm.

5.7.4 Biphenyl-4-carbonitrile (243)[44]



$C_{13}H_9N$
Mol. Wt.: 179.2

243

GP6: $Pd(dba)_2$ (0.006 g, 0.02 mmol); phenylboronic acid (0.183 g, 1.5 mmol); KF (0.174 g, 3.0 mmol); diphenyl(2,2,2-triferrocenylethyl)phosphine (**58**) (2 mL, 0.01 M in THF, 0.02 mmol); 4-chlorobenzonitrile (0.137 g, 1.0 mmol); column chromatography (SiO_2, 25 x 2 cm, PE / EE 10:1) gave pure biphenyl-4-carbonitrile (**243**) (0.171 g, 0.9 mmol, 95 %).

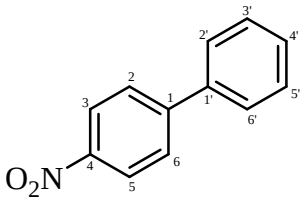
GP5: $Pd(dba)_2$ (0.006 g, 0.02 mmol); phenylboronic acid (0.183 g, 1.5 mmol); KF (0.174 g, 3.0 mmol); diphenyl(2,2,2-triferrocenylethyl)phosphine (**58**) (2 mL, 0.01 M in THF, 0.02

mmol); 4-chlorobenzonitrile (0.137 g, 1.0 mmol); 60 - 65 °C; 72 h; column chromatography (SiO_2, 25 x 2 cm, PE / EE 10:1) gave pure biphenyl-4-carbonitrile (**243**) (0.164 g, 0.9 mmol, 92 %).

GP5: $Pd(dba)_2$ (0.006 g, 0.02 mmol); phenylboronic acid (0.183 g, 1.5 mmol); KF (0.174 g, 3.0 mmol); diphenyl(2,2,2-triferrocenylethyl)phosphine (**58**) (2 mL, 0.01 M in THF, 0.02 mmol); 4-bromobenzonitrile (0.182 g, 1.0 mmol); 60 - 65 °C; 19 h; column chromatography (SiO_2, 25 x 2 cm, PE / EE 10:1) gave pure biphenyl-4-carbonitrile (**243**) (0.171 g, 0.9 mmol, 95 %).

243: ^{1}H NMR (200 MHz, $CDCl_3$): δ = 7.46 - 7.57 (m, 3H, Ph), 7.60 - 7.77 (m, 6H, Ph) ppm. - ^{13}C NMR (50 MHz, APT, $CDCl_3$): δ = 110.7 (+, C-4), 118.7 (+, CN), 127.0 (–, C-2', C-6'), 127.5 (–, C-2, C-6), 128.5 (–, C-4'), 128.9 (–, C-3', C-5'), 132.4 (–, C-3, C-5), 138.9 (+, C-1'), 145.4 (+, C-1) ppm.

5.7.5 4-Nitrobiphenyl (244)[44]



$C_{12}H_9NO_2$
Mol. Wt.: 199.2

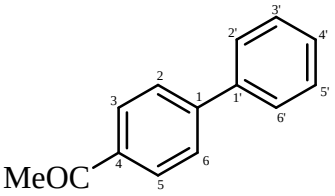
244

GP5: $Pd(dba)_2$ (0.006 g, 0.02 mmol); phenylboronic acid (0.183 g, 1.5 mmol); KF (0.174 g, 3.0 mmol); diphenyl(2,2,2-triferrocenylethyl)phosphine (**58**) (2 mL, 0.01 M in THF, 0.02 mmol); 1-bromo-4-nitrobenzene (0.202 g, 1.0 mmol); 60 - 65 °C; 72 h; column chromatography (SiO_2, 25 x 2 cm, PE) gave pure 4-nitrobiphenyl (**244**) (0.193 g, 0.9 mmol, 97 %).

244: ^{1}H NMR (200 MHz, $CDCl_3$): δ = 7.43 - 7.47 (m, 3H, Ph), 7.57 - 7.61 (m, 2H, Ph), 7.66 - 7.71 (m, 2H, Ph), 8.22 - 8.27 (m, 2H, Ph) ppm. - ^{13}C NMR (50 MHz, APT, $CDCl_3$): δ =

124.6 (–, C-3, C-5), 127.9 (–, C-2', C-6'), 128.3 (–, C-2, C-6), 129.4 (–, C-4'), 129.7 (–, C-3', C-5'), 139.2 (+, C-1'), 147.6 (+, C-1), 148.1 (+, C-4) ppm.

5.7.6 1-Biphenyl-4-yl-ethanone (245)[44]



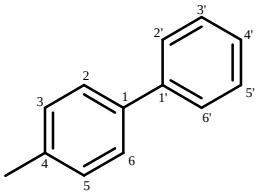
$C_{14}H_{12}O$
Mol. Wt.: 196.2

245

GP6: $Pd(dba)_2$ (0.006 g, 0.02 mmol); phenylboronic acid (0.183 g, 1.5 mmol); KF (0.174 g, 3.0 mmol); diphenyl(2,2,2-triferrocenylethyl)phosphine (**58**) (2 mL, 0.01 M in THF, 0.02 mmol); 1-(4-bromophenyl)ethanone (0.199 g, 1.0 mmol); column chromatography (SiO_2, 25 x 2 cm, PE / EE 15:1) gave pure 1-biphenyl-4-yl-ethanone (**245**) (0.190 g, 1.0 mmol, 97 %).

245: ^{1}H NMR (200 MHz, $CDCl_3$): δ = 2.57 (s, 3H, CH_3), 7.37 - 7.41 (m, 3H, Ph), 7.54 - 7.64 (m, 4H, Ph), 7.95 - 7.99 (m, 2H) ppm. - ^{13}C NMR (50 MHz, APT, $CDCl_3$): δ = 26.5 (-, COMe), 127.0 (–), 127.1 (–), 128.1 (–), 128.78 (–), 128.83 (–), 135.7 (+), 139.7 (+), 145.6 (+), 197.6 (+, CO) ppm.

5.7.7 4-Methylbiphenyl (246)[44]



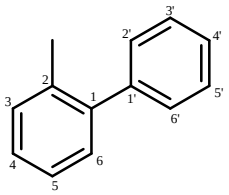
$C_{13}H_{12}$
Mol. Wt.: 168.2

246

GP6: $Pd(dba)_2$ (0.006 g, 0.02 mmol); phenylboronic acid (0.183 g, 1.5 mmol); KF (0.174 g, 3.0 mmol); diphenyl(2,2,2-triferrocenylethyl)phosphine (**58**) (2 mL, 0.01 M in THF, 0.02 mmol); 4-bromotoluene (0.12 mL, 1.0 mmol); column chromatography (SiO_2, 25 x 2 cm, PE / EE 15:1) gave pure 4-methylbiphenyl (**246**) (0.087 g, 0.5 mmol, 52 %).

246: ^{1}H NMR (200 MHz, $CDCl_3$): δ = 2.36 (s, 3H, CH_3), 7.19 - 7.6 (m, 9H, Ph) ppm. - ^{13}C NMR (50 MHz, APT, $CDCl_3$): δ = 21.0 (–, Me), 126.93 (–), 126.96 (–), 128.7 (–), 129.4 (–), 136.9 (+), 138.3 (+), 141.1 (+) ppm.

5.7.8 2-Methylbiphenyl (247)[44]



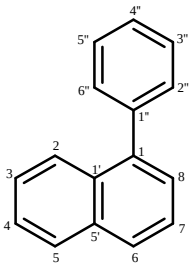
$C_{13}H_{12}$
Mol. Wt.: 168.2

247

GP6: $Pd(dba)_2$ (0.006 g, 0.02 mmol); phenylboronic acid (0.183 g, 1.5 mmol); KF (0.174 g, 3.0 mmol); diphenyl(2,2,2-triferrocenylethyl)phosphine (**58**) (2 mL, 0.01 M in THF, 0.02 mmol); 2-bromotoluene (0.12 mL, 1.0 mmol); column chromatography (SiO_2, 25 x 2 cm, PE / EE 15:1) gave pure 2-methylbiphenyl (**247**) (0.128 g, 0.8 mmol, 77 %).

247: ^{1}H NMR (200 MHz, $CDCl_3$): δ = 2.37 (s, 3H, CH_3), 7.32 - 7.5 (m, 9H, Ph) ppm. - ^{13}C NMR (50 MHz, APT, $CDCl_3$): δ = 20.4 (–, Me), 125.7 (–), 126.7 (–), 127.2 (–), 128.0 (–), 129.1 (–), 129.8 (–), 130.3 (–), 135.3 (+), 141.94 (+), 141.96 (+) ppm.

4.7.9 1-Phenylnaphthalene (248)[44]



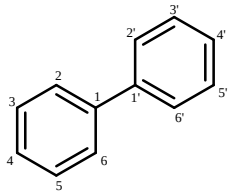
$C_{16}H_{12}$
Mol. Wt.: 204.3

248

GP6: $Pd(dba)_2$ (0.006 g, 0.02 mmol); phenylboronic acid (0.183 g, 1.5 mmol); KF (0.174 g, 3.0 mmol); diphenyl(2,2,2-triferrocenylethyl)phosphine (**58**) (2 mL, 0.01 M in THF, 0.02 mmol); 1-bromonaphthalene (0.18 mL, 1.29 mmol); column chromatography (SiO_2, 25 x 2 cm, PE) gave pure 1-phenylnaphthalene (**248**) (0.163 g, 0.8 mmol, 62 %).

248: ^{1}H NMR (200 MHz, $CDCl_3$): δ = 7.31 - 7.45 (m, 9H, Ph), 7.64 - 7.90 (m, 3H, Ph) ppm. - ^{13}C NMR (50 MHz, APT, $CDCl_3$): δ = 125.3 (–), 125.7 (–), 125.98 (–), 125.99 (–), 126.9 (–), 127.2 (–), 127.6 (–), 128.2 (–), 130.0 (–), 131.6 (+, C-1’ or C-5’), 133.8 (+, C-1’ or C-5’), 140.2 (+, C-1 or C-1’’), 140.7 (+, C-1 or C-1’’) ppm.

5.7.10 Biphenyl (249)[44]



$C_{12}H_{10}$
Mol. Wt.: 154.2

249

GP5: $Pd(OAc)_2$ (0.005 g, 0.02 mmol); phenylboronic acid (0.183 g, 1.5 mmol); $CsCO_3$ (0.977 g, 3.0 mmol); diphenyl(2,2,2-triferrocenylethyl)phosphine (**58**) (2 mL, 0.01 M in THF, 0.02 mmol); bromobenzene (0.1 mL, 1.0 mmol); 60 – 65 °C; 24 h; column chromatography (SiO_2, 25 x 2 cm, PE) gave pure biphenyl (**249**) (0.035 g, 0.2 mmol, 23 %).

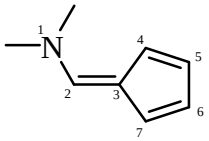
GP5: $Pd(OAc)_2$ (0.005 g, 0.02 mmol); phenylboronic acid (0.183 g, 1.5 mmol); KF (0.174 g, 3.0 mmol); diphenyl(2,2,2-triferrocenylethyl)phosphine (**58**) (2 mL, 0.01 M in THF, 0.02 mmol); bromobenzene (0.1 mL, 1.0 mmol); 80 °C; 24 h; column chromatography (SiO_2, 25 x 2 cm, PE) gave pure biphenyl (**249**) (0.070 g, 0.5 mmol, 46 %).

GP5: $Pd(dba)_2$ (0.006 g, 0.02 mmol); phenylboronic acid (0.183 g, 1.5 mmol); KF (0.174 g, 3.0 mmol); diphenyl(2,2,2-triferrocenylethyl)phosphine (**58**) (2 mL, 0.01 M in THF, 0.02 mmol); bromobenzene (0.142 g, 1.0 mmol); 60 - 65 °C; 19 h; column chromatography (SiO_2, 25 x 2 cm, PE) gave pure biphenyl (**249**) (0.077 g, 0.5 mmol, 54 %).

249: ^{1}H NMR (200 MHz, 297 K, $CDCl_3$): δ = 7.32 - 7.46 ppm (m, 6H), 7.56 - 7.61 (m, 4H).

5.8 [1,1]-Ferrocenophane Derivatives

5.8.1 Cyclopenta-2,4-dienylidenemethyldimethylamine (185)[132]



$C_8H_{11}N$
Mol. Wt.: 121.2

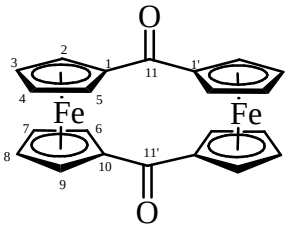
185

At 25 °C freshly cut sodium (10.000 g, 0.4 mmol) was added to dicyclopentadiene (**189**) (400.00 mL, 2.9 mmol) in nitrogen. This suspension was heated at reflux for 6 h under nitrogen. On heating, a white solid precipitated. The reaction mixture was filtered warm in nitrogen and the white solid washed with anhydrous hexane to give pure sodium cyclopentadienide (**186**) which was used without further purification.[133]

To *N*,*N*-dimethylformamide (**190**) (31.00 mL, 0.4 mmol), dimethyl sulfate (54.18 mL, 0.8 mmol) was slowly added with vigorous stirring under nitrogen at 50 – 60 °C. After the addition is complete, the mixture is heated for 2h at 70 – 80°C, to give the *N*,*N*-dimethylformamide-dimethyl sulfate complex **187** as a viscous pale yellow oil which was used without further purification.[132]

At –10 °C a vigorous stirred solution of sodium cyclopentadienide (**186**) in 300 mL of anhydrous THF was treated with *N*,*N*-dimethylformamide-dimethyl sulfate complex **187**. During the addition the temperature was kept below –5°C. After the addition was complete, the mixture was stirred at 25 °C for 2h. The solution was filtered from the precipitated sodium methyl sulfate, which was washed with THF. The combined organic solutions were concentrated at reduced pressure and the crude product was recrystallized from PE after treatment with activated carbon, to give pure 6-(dimethylamino)fulvene **185** (50.200 g, 0.4 mmol, 95 %) as a orange-yellow solid, identified by comparison with an authentic sample (^{1}H NMR).[132]

5.8.2 [1,1]-Ferrocenophane-1,12-dione (191)[110, 129]



$C_{22}H_{16}Fe_2O_2$
Exact Mass: 424.0

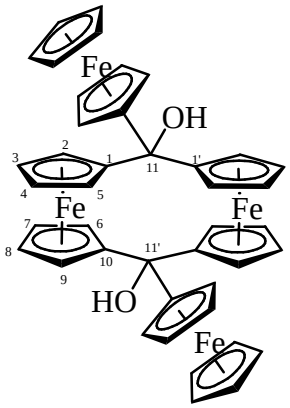
191

At 25 °C, to a well stirred solution of DDQ (2.900 g, 12.7 mmol) in 1 L of CH_2Cl_2, [1,1]-ferrocenophane (**184**) (0.598 g, 1.5 mmol) in 200 mL CH_2Cl_2 was added dropwise, and the solution immediately darkened. The reaction mixture was stirred at 25 °C for 2 h before hydrolysis was performed by addition of 200 mL of MeOH. The reaction mixture was washed with 200 mL of a 1.0 M aqueous solution of NaOH until the aqueous layer was colourless, washed with 200 mL of H_2O, dried over $MgSO_4$ and the solvent was removed at reduced pressure. Column chromatography (neutral aluminum oxide, 25 x 4 cm, CH_2Cl_2 / EE 9:1), gave pure [1,1]-ferrocenophane-1,12-dione (**191**) (0.490 g, 1.2 mmol, 76 %), identified by comparison with an authentic sample (^{1}H NMR).[110, 129] Recrystallization from $CHCl_3$ / hexane gave pure crystals suitable for an X-ray structure analysis.

191: ^{1}H NMR (200 MHz, $CDCl_3$): δ = 4.5 + 5.27 (AA'BB' line system, 2 x 8H, CpR) ppm. - MS (70 eV, 240°C): *m / z*: 425 (50) [M^++H], 243 (100), 330 (41) [M^+–COCp], 304 (53) [M^+–CpFe].

Crystal Structure Analysis of **191:** $C_{22}H_{16}Fe_2O_2$, molecular weight, 424.05 g / mol, temperature 300(2) K, Wavelength 0.71073 Å, crystal system triclinic, space group P^{-1}, a = 6.053(1), b = 14.224(2), c = 14.703(2) Å, α = 71.12(2)°, β = 87.26(2)°, γ = 89.66(2)°, V = 1196.4(3) Å^3, Z = 3, $\rho_{calcd.}$ = 1.767 g cm^{-3}, F(000) = 648, Absorption coefficient = 1.833 mm^{-1}, crystal size 0.96 x 0.04 x 0.03 mm, Stoe IPDS area detector diffractometer, θ-range = 2.42 to 26.20°, limiting indices –7<=h<=7, –17<=k<=17, –18<=l<=18, reflections collected / unique 17203 / 4404 [R(int) = 0.0623], completeness of data(θ = 26.20): 93.2%, no absorption correction, no extinction correction, refinement method Full-matrix least-squares on F^2, goodness-of-fit on F^2 = 1.118, R_1 = 0.0636, wR_2 = 0.1368 (I>2 σ (I)), R-indices[all data]: R_1 = 0.1044, wR_2 = 0.1458, minimal and maximal residual electron density – 0.600 / 0.585 eÅ^{-3}.

5.8.3 *exo,exo*-1,12-Diferrocenyl-[1,1]-ferrocenophane-1,12-diol (214)



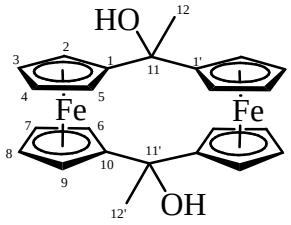
$C_{42}H_{36}Fe_4O_2$
Exact Mass: 796,0

exo,exo-**214**

At 25 °C a well stirred solution of [1,1]-ferrocenophane-1,12-dione (**191**) (0.050 g, 0.1 mmol) in 25 mL of anhydrous THF was treated with of 1,1´-dilithioferrocene [from ferrocene (**14**) (1.00 g, 5.4 mmol), TMEDA (2.20 mL, 14.6 mmol), BuLi (9.00 mL, 1.6 M in hexane, 14.4 mmol) in 12.5 mL of anhydrous hexane].[109] After 1 h at 25 °C, hydrolysis was performed by addition of 10 mL of H_2O. The reaction mixture was diluted with 50 ml of CH_2Cl_2, and the organic layer was washed with 3 x 25 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (SiO_2 deactivated with Et_3N 5% in PE, 25 x 4 cm, PE / CH_2Cl_2 7:3), gave pure *exo,exo*-1,12-diferrocenyl-[1,1]-ferrocenophane-1,12-diol (**214**) (0.068 g, 0.1 mmol, 73 %).

***exo,exo*-214:** ^{1}H NMR (400 MHz, $CDCl_3$): δ = 3.83 (m, 4H, CpR), 3.94 (m, 4H, CpR), 4.05 (s, 10H, CpH), 4.27 (m, 8H, CpR), 4.58 (m, 4H, CpR), 4.67 (m, 4H, CpR), 4.90 (s, 2H, OH) ppm. - ^{13}C NMR (100 MHz, BB, HMQC, HMBC, 297 K, $CDCl_3$): δ = 66.1 (*C*H-CpR), 67.0 (*C*H-CpR), 67.1 (*C*H-CpR), 67.3 (*C*H-CpR), 67.7 (*C*H-CpR), 68.7 (*C*H-CpH), 70.2 (*C*H-CpR), 70.7 (*C*R-CpR), 97.1 (*C*R-CpR), 103.0 [C-11(11´)] ppm. - MS (ESI, ES^+): *m / z*: 796 [M^+], 779 [M^+–OH]. - HRMS (ESI) ($C_{42}H_{36}Fe_2O_2$): calcd. 796.0113; found: 796.0103 [M].

5.8.4 *exo,exo*-1,12-Dimethyl-[1,1]-ferrocenophane-1,12-diol (206)[110]

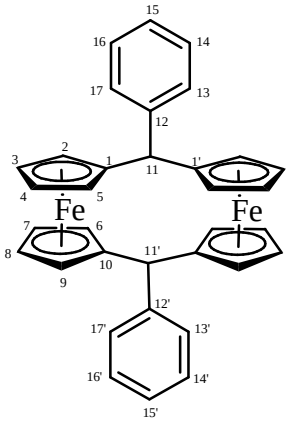


$C_{24}H_{24}Fe_2O_2$
Exact Mass: 456.0

exo,exo-**206**

At 25 °C a well stirred solution of [1,1]-ferrocenophane-1,12-dione (**191**) (0.050 g, 0.1 mmol) and $AlCl_3$ (0.039 g, 0.3 mmol) in 20 mL of anhydrous THF was treated with MeLi (1.00 mL, 1.6 M in DEE, 1.6 mmol). After 1h at 25 °C hydrolysis was performed by addition of 10 mL of H_2O. The reaction mixture was diluted with 50 ml of CH_2Cl_2, and the organic layer was washed with 3 x 25 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (neutral aluminum oxide , 25 x 2 cm, EE), gave pure *exo,exo*-1,12-dimethyl-[1,1]-ferrocenophane-1,12-diol (**206**) (0.047 g, 0.1 mmol, 87 %), identified by comparison with an authentic sample (^{1}H NMR).[110]

5.8.5 *exo,exo*-1,12-Diphenyl-[1,1]-ferrocenophane (207)[110]



$C_{34}H_{28}Fe_2$
Mol. Wt.: 548,3

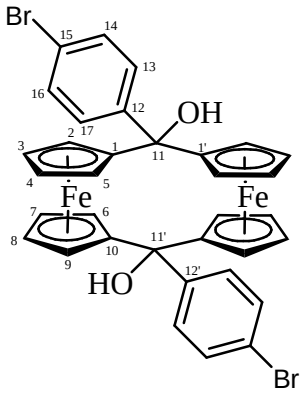
exo,exo-**207**

At 25 °C a well stirred solution of [1,1]-ferrocenophane-1,12-dione (**191**) (0.121 g, 0.3 mmol) in 100 mL of anhydrous THF was treated with of phenyllithium (1 mL, 1.8 M in

cyclohexane, 1.8 mmol). After 1h at 25 °C, $AlCl_3$ (0.90 g, 0.7 mmol) and $LiAlH_4$ (0.098 g, 2.5 mmol) were added and the suspension stirred for 1 h. Hydrolysis was performed by slowly addition of 10 mL of H_2O. The reaction mixture was diluted with 50 ml of PE, and the organic layer was washed 3 x 25 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (neutral aluminum oxide, 25 x 2 cm, PE / CH_2Cl_2 3:1), gave pure *exo,exo*-1,12-diphenyl-[1,1]-ferrocenophane (**207**) (0.065 g, 0.2 mmol, 39 %), identified by comparison with an authentic sample (^{1}H NMR).[110]

***exo,exo*-207**: ^{1}H NMR (200 MHz, $CDCl_3$): δ = 4.20 (m, 4H, CpR), 4.35 (m, 4H, CpR), 4.42 (m, 4H, CpR), 4.75 (m, 4H, CpR), 5.20 [s, 2H, 11(11´)-H], 7.00 - 7.20 (m, 10H, Ph) ppm.

5.8.6 *exo,exo*-1,12-Di(4-bromophenyl)-[1,1]-ferrocenophane-1,12-diol (208)



$C_{34}H_{26}Br_2Fe_2O_2$
Exact Mass: 735,9

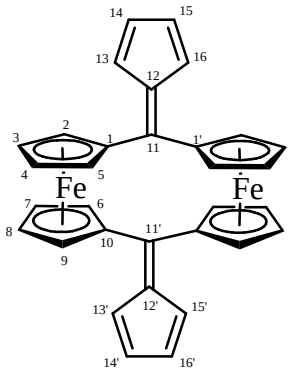
exo,exo-**208**

At 25 °C a well stirred solution of [1,1]-ferrocenophane-1,12-dione (**191**) (0.070 g, 0.2 mmol) and $AlCl_3$ (0.105 g, 0.8 mmol) in 50 mL of anhydrous THF was treated with of 4-bromo-1-lithiobenzene [from 1,4-dibromobenzene (0.500 g, 2.1 mmol), *tert*-BuLi (2.35 mL, 1.7 M in pentane, 4.0 mmol) in 20 mL of anhydrous THF]. After 1h at 25 °C, $LiAlH_4$ (0.300 g, 8.0 mmol) was added in nitrogen and the suspension stirred for 1h. Hydrolysis was performed by slowly addition of 10 mL of H_2O. The reaction mixture was diluted with 50 ml of PE, and the organic layer was washed with 3 x 25 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (neutral aluminum oxide,

25 x 2 cm, PE / CH_2Cl_2 3:1), gave pure *exo,exo*-1,12-di(4-bromophenyl)-[1,1]-ferrocenophane (**208**) (0.120 g, 0.2 mmol, 98 %) as a yellow solid (mp > 200 °C, *decomp*.).

***exo,exo*-208**: IR (ATR): $\tilde{\nu}$ = 3450 (w, OH), 3318 (w, OH), 2963 (w), 2924 (w), 2853 (w). - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 4.20 (m, 4H, CpR), 4.37 (m, 8H, CpR), 4.71 (m, 4H, CpR), 4.91 (s, 2H, OH), 7.02 (d, ^3J = 6.76 Hz, 4H, Ph), 7.19 (d, ^3J = 6.76 Hz, 4H, Ph) ppm. - ^{13}C NMR (100 MHz, BB, HMQC, HMBC, $CDCl_3$): δ = 66.1 (–, *C*H-CpR), 68.2.9 (–, *C*H-CpR), 68.7 (–, *C*H-CpR), 70.2 (–, *C*H-CpR), 73.4 (+, *C*R-CpR), 98.1 [+, C-11(11´)], 120.1 [–, C-12(12´)], 126.6 [–, C-13(13´, 17, 17´)], 130.7 [–, C-14(14´, 16, 16´)], 149.6 [+, C-15(15´)] ppm. - MS (ESI, ES^+): *m / z*: 738 [$M+H^+$], 658 [$M+H^+$–Br]. - HRMS (ESI) ($C_{34}H_{26}Br_2Fe_2O_2$): calcd. 735.8998; found: 735.9000 [M].

5.8.7 1,12-Dicyclopentadienylidene-[1,1]-ferrocenophane (218)



218

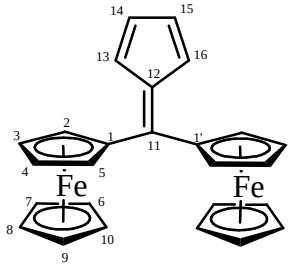
$C_{32}H_{24}Fe_2$
Exact Mass: 520.1

At 25 °C a well stirred solution of [1,1]-ferrocenophane-1,12-dione (**191**) (0.144 g, 0.3 mmol) and $AlCl_3$ (0.180 g, 1.4 mmol) in 50 mL of anhydrous THF was treated with lithium cyclopentadienide [from cyclopentadiene (0.28 mL, 3.4 mmol), *n*-BuLi (2.10 mL, 1.6 M in hexane, 3.4 mmol) in 10 mL of anhydrous DEE]. After 1h at 25 °C an excess of $AlCl_3$ was added (0.60 g, 4.6 mmol) and the reaction mixture was stirred for 1 h at 25 °C. At this point hydrolysis was performed by addition of 10 mL of H_2O, the organic layer was washed with 3 x 25 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (basic aluminum oxide Grade IV, 25 x 4 cm, PE / CH_2Cl_2 7:3), gave

pure 1,12-dicyclopentadienylidene-[1,1]-ferrocenophane (**218**) (0.174 g, 0.3 mmol, 98 %), as a red-black liquid.

218: IR (ATR): $\tilde{\nu}$ = 2956 cm^{-1} (s), 2925 (s), 2857 (s, CH); 1725 (s), 1261 (s). - ^{1}H NMR (400 MHz, $CDCl_3$): δ = 4.54 + 4.99 (AA'BB' line system, 2 x 8H, CpR), 6.31 - 6.34 [m, 4H, 13-(16, 13', 16')-H or 14-(15, 14', 15')-H], 6.44 - 6.45 [m, 4H, 13-(16, 13', 16')-H or 14-(15, 14', 15')-H] ppm. - ^{13}C NMR (100 MHz, BB, HMQC, HMBC, $CDCl_3$): δ = 70.4 (*C*H-CpR), 75.9 (*C*H-CpR), 86.0 (*C*R-CpR), 123.9 [C-13(16) or C-14(15) and C-13'(16') or C-14'(15')], 129.8 [C-13(16) or C-14(15) and C-13'(16') or C-14'(15')], 144.9 [C-12(12') or C-11(11')], 147.9 [C-12(12') or C-11(11')] ppm. - MS (ESI, ES^+): *m / z*: 521 [$M+H^+$]. - HRMS (ESI) ($C_{32}H_{25}Fe_2$): calcd. 521.0655; found 521.0641 [M+H].

5.8.8 1-Cyclopentadienylidenediferrocenylmethane (202)

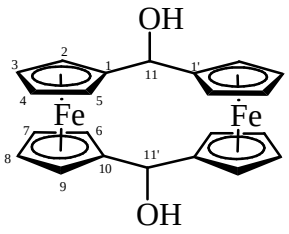


$C_{26}H_{22}Fe_2$
Exact Mass: 446.0

202

At 25 °C a well stirred solution of diferrocenylketone (**40**) (0.110 g, 0.3 mmol) and $AlCl_3$ (0.066 g, 0.5 mmol) in 20 mL of anhydrous THF was treated with lithium cyclopentadienide [from cyclopentadiene (0.04 mL, 0.5 mmol), BuLi (0.30 mL, 1.6 M in hexane, 0.5 mmol) in 10 mL of DEE)]. After 1h at 25 °C hydrolysis was performed by addition of 10 mL of H_2O. The organic layer was washed 3 x 25 mL of 3 M aqueous HCl, 25 mL of saturated solution of $NaHCO_3$, 25 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Column chromatography (basic aluminum Grade IV, 25 x 2 cm, PE / CH_2Cl_2 2:1), gave pure 1-cyclopentadienylidenediferrocenylmethane (**202**) (0.122 g, 0.3 mmol, 99 %), identified by comparison with an authentic sample (^{1}H NMR).[40, 123]

5.8.9 *endo,exo*- and *exo,exo*-[1,1]-Ferrocenophane-1,12-diol (205)[110]



$C_{22}H_{20}Fe_2O_2$
Exact Mass: 428.0

endo,exo- and *exo,exo*-**205**

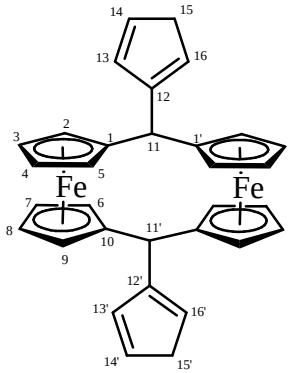
At 25 °C a well stirred solution of [1,1]-ferrocenophane-1,12-dione (**191**) (0.050 g, 0.1 mmol) in 100 mL of anhydrous THF, was treated with $LiALH_4$ (0.076 g, 2.0 mmol). After standing at 25 °C for 2h, hydrolysis was performed with 10 mL of H_2O. The organic layer was washed with 3 x 20 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. Precipitation from CH_2Cl_2 with PE, gave a 2:1 mixture of *endo,exo*- and *exo,exo*-[1,1]-ferrocenophane-1,12-diol (**205**) (0.025 g, 0,06 mmol, 50 %).[110]

***exo,exo*-205**: ^{1}H NMR (200 MHz, 297 K, $CDCl_3$): δ = 4.27 (s, 8H, CpR), 4.46 (s, 8H, CpR), 5.18 (s, 1H, C-11 or C-11'), 5.3 (s, 1H, C-11 or C-11').

***endo,exo*-205:** ^{1}H NMR (200 MHz, 297 K, $CDCl_3$): δ = 4.33 (s, 8H, CpR), 4.52 (s, 8H, CpR), 5.37 [s, 2H, C-11(11')].

205: IR (ATR): $\tilde{\nu}$ = 3300 cm^{-1} (b, -OH), 3092 (w, Cp-H), 2962 (s), 2925 (s), 2851, (s, CH).

5.8.10 *endo,exo*- and *exo,exo*-1,12-Di(cyclopenta-1,3-dienyl)-[1,1]-ferrocenophane (221)



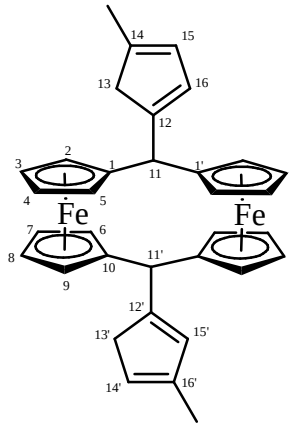
$C_{32}H_{28}Fe_2$
Exact Mass: 524,09

endo,exo- and *exo,exo*-**221**

At 25°C a well stirred solution of 1,12-dicyclopentadienylidene-[1,1]-ferrocenophane (**218**) (0.050 g, 0.1 mmol) in 10 mL of anhydrous THF, was treated with $LiAlH_4$ (0.060 g, 1.6 mmol) and was allowed to react over 3 d at 25 °C. Hydrolysis was performed by addition of 10 mL of H_2O, and the organic layer was diluted with 50 mL of DEE, washed with 3 x 25 mL of H_2O, dried over $MgSO_4$, and the solvent was removed at reduced pressure. The yellow-orange solid was washed with cold DEE to give a 1:1 mixture of *endo,exo*- and *exo,exo*-1,12-di(5-cyclopenta-1,3-dienyl)-[1,1]-ferrocenophane (**221**) (0.045 g, 0.085 mmol, 90 %).

***endo,exo*- and *exo,exo*-221:** ^{1}H NMR (400 MHz, 297 K, $CDCl_3$): δ = 2.48 (s, 4H, C_5H_5), 2.77 (s, 4H, C_5H_5), 4.13 (m, 16H, CpR), 4.25 (s, 8H, CpR), 4.39 (s, 4H, CpR), 4.42 (s, 4H, CpR), 4.61 (s, 2H, 11-H or 11´-H), 4.65 (s, 2H, 11-H or 11´-H), 5.73 (s, 2H, C_5H_5), 5.98 (s, 2H, C_5H_5), 6.05 (m, 2H, C_5H_5), 6.15 - 6.2 (m, 6H, C_5H_5) ppm. - ^{13}C NMR (100 MHz, BB, HMQC, HMBC, $CDCl_3$): δ = 40.8 [C_5H_5 or C-11(11´)], 40.9 [C_5H_5 or C-11(11´)], 41.12 [C_5H_5 or C-11(11´)], 41.15 [C_5H_5 or C-11(11´)], 41.9 [C_5H_5 or C-11(11´)], 66.88 (*C*H-CpR), 66.91 (*C*H-CpR), 67.0 (*C*H-CpR), 68.89 (*C*H-CpR), 68.91 (*C*H-CpR), 69.9 (*C*H-CpR), 70.0 (*C*H-CpR), 91.8 (*C*R-CpR), 92.5 (*C*R-CpR), 124.26 (C_5H_5), 124.27 (C_5H_5), 131.1 (C_5H_5), 131.8 (C_5H_5), 133.17 (C_5H_5), 133.19 (C_5H_5), 133.5 (C_5H_5), 153.1 (C_5H_5), 156.0 (C_5H_5) ppm. - MS (ESI, ES^+): *m / z*: 524 [M^+], 459 [M^+–C_5H_5]. - HRMS (ESI) ($C_{32}H_{28}Fe_2$): calcd. 524.0890; found 524.0897 [M]. - HRMS (ESI) ($C_{27}H_{23}Fe_2$): calcd. 459.0499; found 459.0514 [M-C_5H_5].

5.8.11 *endo,exo*- and *exo,exo*-1,12-Di(methylcyclopenta-1,3-dienyl)-[1,1]-ferrocenophane (220)



$C_{34}H_{32}Fe_2$
Exact Mass: 552,1

endo,exo- and *exo,exo*-**220**

At 25°C a well stirred solution of *endo,exo*- and *exo,exo*-1,12-di(5-cyclopenta-1,3-dienyl)-[1,1]-ferrocenophane (**221**) (0.097 g, 0.2 mmol) in 200 mL of anhydrous THF, was treated with BuLi (0.25 mL, 1.6 M in hexane, 0.4 mmol) and was allowed to react for 1 h. An aliquot from the reaction mixture was taken and added to an excess of MeI. Hydrolysis was performed by addition of H_2O, and the organic layer was investigated by mass spectrometry.

***endo,exo*- and *exo,exo*-220:** MS (ESI, ES^+): *m / z*: 552 [M^+]. - HRMS (ESI) ($C_{34}H_{32}Fe_2$): calcd. 552.1203; found 552.1199 [M].

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