Efficient & Novel Approaches to Relay Chirality in the Synthesis of Planar Chiral Metallocenes

Jahangir Amin

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Abstract

Intermolecular and intramolecular dynamic kinetic resolution were detected for organocobalt complexed diynes prepared from the complexation of an alkyne to dicobalt hexacarbonyl, $Co_2(CO)_6$ and subsequent manipulation of the carbocationic charge generated at the carbon α– to the alkyne moiety *via* to the prior treatment with a $Co_2(CO)_6$– stabilised enyne, propargylic alcohol and alkynyl radical in a interesting departure from the Nicholas reaction. Diastereomeric ratios of up to 1:0 in favour of the *anti* diastereoisomer and yields of up to 67% were observed.

Ether and ester linked diynes were synthesised from secondary terminal propargylic alcohols. On heating with (η5– cyclopentadienyl)*bis*(triphenylphosphine)cobalt(I), new chiral transition metal complexes were formed with high diastereomeric ratios in greater than 70% yield displaying in some cases four elements of chirality; central carbon chirality, chiral–at–metal chirality, conformational propeller phosphine chirality and conformational atropisomerism. Using mainly two representative examples the first a 7,5–membered cyclic lactone and the second a 5,5–membered cyclic ether complex the origins of chirality were explored which indicated the central carbon chirality relayed its stereochemical information to the stereogenic transition metal center thus resulting in a opposite configuration to the remote central carbon element of chirality *i.e.* (S_C,R_{Co}). Due to the unique properties of the 7,5–membered cyclic lactone complex a relatively stable major conformation propeller isomer of triphenylphosphine was found to be locked in space *e.g.* (S_C,R_{Co},P). NMR analysis showed the presence of a dynamic equilibrium as three minor peaks of approximate equal intensity were observed which could be conformational atropisomers arising from hindered rotation between two interacting aromatics as a result of conformational flexibility inherent of the lactone architecture *e.g.* ($P,_aR$), ($R,_aS$), ($M,_aR$), ($M,_aS$).

With respect to the 5,5–membered cyclic ether complex using a chiral ether diyne in a oxidative cyclisation reaction was found to result in chirality being relayed from the carbon stereogenic center to the chiral–at–metal stereocenter. As with the lactone complexes, an opposite configuration was observed. However, with respect to the conformation of triphenylphosphine it appeared to be non selective upon initial complexation. Recrystallisation gave an enriched (*M*) propeller conformational isomer which allowed the configurational stability of the chiral metal center to be measured which suggested that a mechanism did exist for epimerisation at metal but occurred only at an ambient temperature over several hours.

Chiral metallocyclopentadiene complexes were treated with a selection of isocyanides and found to give novel planar chiral (η5–cyclopentadienyl)(η4–iminocyclopentadiene)cobalt metallocenes in good yields >60% yield and in some cases a diastereomeric ratio of up to 5:1. The isocyanide insertion reaction was in some cases complementary to the results observed for the isocyanides isoelectronic equivalent carbon monoxide which gave similar planar chiral (η5– cyclopentadienone)(η5–cyclopentadienyl)cobalt metallocenes. Preliminary results suggests because the isocyanide is smaller, in the diastereomeric transition state it is less discriminating compared to the chiral–at–metal complexes which are highly diastereoselective with respect to the configuration at metal. The methodology was extended to a non racemic example and found which gave a diastereomeric ratio of 2:1 and 92% yield.

Statement of Originality

I certify that this thesis, and the research to which it refers, are the product of my own work therefore I declare:

(i).   This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

(ii).   This thesis is the result of my own investigations, except were otherwise stated, Other sources, ideas or quotations from the work of other people are acknowledged by footnotes giving explicit references. A bibliography is appended.

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Signed………………………………. (Candidate: 3804178)

Jahagnir Amin

Norwich, March 2011

Signed………………………………. (Postgraduate Supervisor)

Dr. Christopher J. Richards

Norwich, March 2011

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Publications

- Synthesis and ^{1}H NMR spectroscopic properties of substituted (η^4–tetraarylcyclobutadiene)(η^5–cyclopentadienyl) cobalt metallocenes; Huy V. Nguyen, Mebuba R. Yeamine, **Jahangir Amin**, Majid Motevalli and Christopher J. Richards; *Journal of Organometallic Chemistry*, 693, 24, **2008**, p. 3668–3676.

Abbreviations

Anal.	Elemental analysis
APCI	Atmospheric pressure chemical ionisation
app.	Apparent
Ar	Aromatic
ARCM	Asymmetric ring closing metathesis
Bu	Butyl
BINAP	2,2'–bis(diphenylphosphino)–1,1'-binaphthyl
C	Cyclo
°C	Celsius
ca.	*Circa*
Calc.	Calculated
Cat.	Catalytic
CBS	Corey–Bakshi–Shibata {(CBS)–catalyst [oxazaborolidine]}
coal.	Coalescence
COD	1,5–Cyclooctadiene
conv.	Conversion
cy	Cyclohexyl
d	Doublet
d.e.	Diastereomeric excess
DABCO	1,4–Diazabicyclo[2.2.2]octane
DBU	1,8–Diazabicyclo[5.4.0]undec–7–ene
DCM	Dichloromethane
dd	Doublet of doublets
decomp.	Decomposition
DET	Diethyl tartrate
(DHQ)$_2$PYR	Hydroquinine 2,5–diphenyl–4,6-pyrimidinediyl diether
(DHQD)$_2$PYR	Hydroquinidine 2,5–diphenyl–4,6-pyrimidinediyl diether
DIBAL–H	Diisobutylaluminium hydride
DiPAMP	((1*S*,2*S*)–(+)–*bis*[(2–methoxyphenyl)phenylphosphino]ethane)
DIPE	diisopropyl ether
DKR	Dynamic kinetic resolution
DMAP	Dimethylaminopyridine
DMF	Dimethylformamide
DMSO	Dimethylsulfoxide
DNA	Deoxyribonucleic acid
d.r.	Diastereomeric ratio
dt	Doublet of triplets
dsept	Doublet of septets
E	Configurational stereochemistry based Cahn Ingold Prelog priority rules
EBI	1,2–(1–indenyl)$_2$ethane

e.e.	Enantiomeric excess
equiv.	Equivalents
ES	Electrospray
Et	Ethyl
FAB	Fast atom bombardment
FT–IR	Fourier transform infra red spectroscopy
G.C.	Gas chromatography
HDMF	2–[(dimethylamino)methyl]–1(1–hydroxyethyl)ferrocene
hrs	Hours
Hz	Hertz
i	Iso
IR	Infra red
LDA	Lithium diisopropyl amide
L	Ligand
L–DOPA	L–3,4-dihydroxyphenylalanine
L_n	No. of ligands
m	Multiplet
m	Meta
M	(+)–Conformational isomer
max	Maximum
Me	Methyl
mol	Mole
m.p.	Melting point
MS	Mass spectrometry
NASID	Non steroidal anti inflammatory drug
NBS	*N*–Bromosuccinimide
NMR	Nuclear magnetic resonance
NOE	Nuclear Overhauser Effect
OAc	Acetate
OTf	Triflate
OTs	Tosylate
p	Para
P	(–)–Conformational isomer
PCpH	Pinene–fused cyclopentadiene
pent	Pentet
Ph	Phenyl
PKR	Pauson Khand reaction
Pr	Propyl
($_p$*R*)	Planar chiral (*R*) stereochemistry
($_p$*S*)	Planar chiral (*S*) stereochemistry
q	Quartet
(*R*)	Absolute (*R*) stereochemistry based on Cahn Ingold Prelog priority rules
(*R*$_a$)	Axially chiral (*R*) stereochemistry

rac	Racemic
RNA	Ribonucleic acid
RT	Room temperature
s	Singlet
(*S*)	Absolute (*S*) stereochemistry based on Cahn Ingold Prelog priority rules
(*S*$_a$)	Axially chiral (*S*) stereochemistry
sat.	Saturated
SBI	(1–indenyl)$_2$SiMe$_2$
tert	Tertiary
t	Triplet
t–BME	*tert*–butyl methyl ether
THF	Tetrahydrofuran
TLC	Thin layer chromatography
TMEDA	Tetramethylethylenediamine
TMS	Trimethylsilyl
TOF	Turn over frequency
TON	Turn over number
Tol	Tolyl
vol.	Volume
Z	Configurational stereochemistry based Cahn Ingold Prelog priority rules
(*)	Relative stereochemistry
(+)	Rotates plane polarised light clockwise
(−)	Rotates plane polarised light anti clockwise

Chapter One:

Chapter Two:

Chapter Three:

Chapter Four:

Chapter One

LITERATURE SURVEY OF THE DIFFERENT METHODS DEVELOPED FOR THE SYNTHESIS OF CHIRAL METALLOCENE COMPLEXES.

1.0   General Introduction to Thesis.

The research detailed in this thesis will communicate the diastereoselective synthesis of chiral organocobalt complexes using the Nicholas reaction, non–racemic chiral–at–cobalt complexes and planar chiral cobalt metallocenes.

The general introduction aims to convey and put into perspective the significance of chirality in general when considering the study and application of molecular sciences, and the important work that is associated with organic, inorganic, natural product, pharmaceutical and analytical chemistry. Following this, a survey of the different protocols for generating planar chirality and in some cases central chirality in metallocenes and ansa metallocenes will be discussed. This review will focus mainly on the synthesis of planar chiral metallocenes and convey the methods that exist to date.

Following the introductory chapter subsequent chapters will be preceded by a short introduction. The objective of these introductions is to highlight the most recent and relevant literature concerning the subject matter. The final chapter will report experimental procedures used and developed, and the characterisation of each molecule and complex synthesised as part of this research. Appendices and a bibliography will follow and give details of data collection and references to the literature.

1.1   Introduction to Chapter One.

In nature there are certain molecules that exist which are required for the sustenance of life. These molecules can be in the form of two distinct entities, otherwise known as enantiomers and by definition are non–supermposible mirror images of one another. The relationship of these enantiomers is referred to as chirality. To determine whether a molecule is either achiral (non chiral) or chiral a logical system is followed *i.e.* if a molecule lacks an *n*–fold rotation (360°/n) followed by a reflection in the plane perpendicular to this axis it is chiral **(Figure 1)**. [1]

Figure 1. (*R*)–alanine can be found in nature {(*R*) refers to the Latin word rectus meaning right, (*S*)–alanine (*S*) refers to the Latin word sinister, meaning left}. [1]

1.1.1 Chirality and Life.

Enantiomers are known to undergo identical chemical reactions; however they behave differently when they interact with a chiral stimulus *e.g.* a receptor site. Chirality is all around us, like in macroscopic objects *e.g.* helically formed

snails, spiralling plants or on a nanoscopic level such as in biologically–active molecules like naturally occurring L–amino acids which are building blocks for proteins.

The significance of chirality can be reiterated with examples like a racemic polypeptide would not be able to form specific shapes for enzymes. Moreover wrong 'handed' amino acids could result in a destabilisation of the α–helixes in proteins and as a consequence genetic coding could not be stored or replicated. Several theories exist to explain the emergence of chirality *e.g.* chirality is as a result of circularly polarised ultraviolet light, β–decay and weak forces in atoms, optically active quartz powders, self selection, fluke seeding, homochiral template, transfer RNAs selected the right enantiomer, magnetic fields and magnetochiral dichroism. The exact inherent origin of homochirality and its presence in nature is unknown. [2], [3]

1.1.2 Chirality in Industry: The Commercial Manufacture and Applications of Optically Active Compounds.

The manufacture of optically active intermediates and/or products as pure enantiomers is of enormous interest in industry and academia as it is associated with cost efficiency and enhanced biological activity. The world market for chiral fine chemicals such as those produced by the pharmaceutical industry was in excess of 80 billion dollars in 1992, and in 2002 was worth 159 billion dollars with approximately 30% sold as single enantiomer drugs, 2/3 small molecules and 1/3 biopharmaceuticals **(Figure 2)** and **(Table 1)**. [4–7] The driving force for this has been as follows. 1). Racemic switches have allowed patent protection to be broken in racemic mixtures of drugs. 2). Biological activity and selectivity of single enantiomers were found to often vary significantly *i.e.* an active isomer often had desirable activities and therefore better pharmacokinetic/metabolic profiles.

(*S*)-(+)-Ibuprofen **(1)**
(*S*)-2-(4-isobutylphenyl)propanoic acid

- Reaches therapeutic concentrations in blood in 12 minutes versus 30 minutes for racemic mixtures.

(*R*)-Floxetine **(2)**
(*R*)-*N*-methyl-3-phenyl-3-[4-(trifluoromethyl) phenoxy]propan-1-amine hydrochloride

- Treatment of depression.
- Pure isomer of Prozac.

(*R*)-Ketoprofen **(3)**
(*R*)-2-(3-benzoylphenyl)propanoic acid

- (*R*)–toothpaste additive to prevent periodontal disease.
- (*S*)–analgesic (NSAID, non–steroidal anti–inflammatory drug).

Figure 2. Structures of well known pharmaceutical drugs. [4–7]

Table 1. Chiral blockbusters. [8]

Brand	Global 2003 sales ($ Billions)	Active ingredients	Form of active ingredients	Therapeutic effect
Lipitor	10.3	Atorvastatin	Single enantiomer	Lipid–lowering agent
Zocor	6.1	Simvastatin	Single enantiomer	Lipid–lowering agent
Zyprexa	4.8	Olanzapine	Achiral	Psychotropic agent
Norvasc	4.5	Amlodipine	Racemate	Calcium channel blocker
Procrit	4.0	Epoetin a	Protien	Stimulant of blood cell production
Prevacid	4.0	Lansoprazole	Racemate	Inhibitor of gastric acid secretions
Nexium	3.8	Esomeprazole	Single enantiomer	Inhibitor of gastric acid secretions
Plavix	3.7	Clopidogrel	Single enantiomer	Inhibitor of gastric acid secretions
Advair	3.7	Salmeterol Fluticasone	Racemate Single enantiomer	β_2–adrenergic bronchodilator Anti–inflammatory agent
Zoloft	3.4	Sertraline	Single enantiomer	Selective serotonin reuptake inhibitor

There are several methods that exist today for the synthesis of enantiopure compounds; the traditional methods include the following. 1). Resolution of racemic mixtures. 2). Synthesis from a chiral pool or synthesis using a chiral auxiliary. [9] The more contemporary methods utilise. 3). Biocatalysts such as enzymes, cell cultures and anti–bodies. [10], [11] 4). Transition metal catalysts. When you consider the traditional methods retrospectively *i.e.* enantiomerically enriched compounds synthesised from either a chemical transformation of an enantiomerically enriched precursor, derived directly or indirectly from natures' chiral pool, or by resolving a racemic (equimolar) mixture or two enantiomers, both methodologies have disadvantages; they are in the case of the former it requires stoiciometric quantities of a suitable precursor and the latter only allows up to 50% of desired enantiomer to be synthesised.

1.1.3 Origins of Metallocene Free Asymmetric Catalysis.

The concept of a chemical substance that participates in multiple chemical transformations but is not consumed by the reaction was envisaged to be a significant advantage over traditional methods. In nature enantiomerically pure compounds have been synthesised by chirality transfer using enzymatic catalysts. However, only relatively recently in the last few decades has asymmetric catalysis enabled enantiomeric excesses (*e.e.*) of up to 100% to be achieved using synthetic catalysts.

The diphosphine DiPAMP ((1*S*,2*S*)–(+)–*bis*[(2–methoxyphenyl)phenylphosphino]ethane) **(7)** first reported in 1968 by W. S. Knowles (¼ Noble prize in Chemistry 2001), is used for the industrial production of L–DOPA **(Scheme 1)**, a drug used to treat Parkinson's disease which is a degenerative disorder of the central nervous system, resulting in impairment of motor skills and speech. The chiral ligand, chelates to the metal center to form an asymmetric catalyst which reacts with an achiral precursor and in doing so transfers its chirality to the reaction product which as a result becomes chiral. High enantiomeric excesses (*e.e.*) have been reported for hydrogenation and the postulated mechanism is illustrated in **Figure 3**, no two orientations face the alkene. In this case hydrogenation occurs *via* the

minor intermediate since it has the low energy pathway to the addition of H_2 *i.e.* the reaction is under kinetic control. The catalyst had high turnover number (TON) and relatively good turn over frequency (TOF). [10]
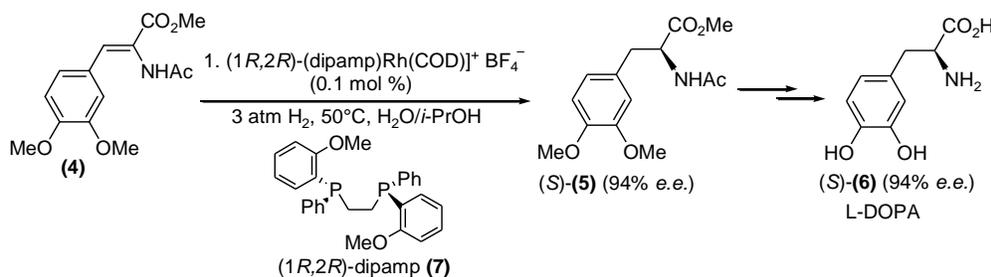
Scheme 1. Industrial application of the chiral catalyst $[(R,R)–(dipamp)Rh(COD)]^+BF_4^-$.[10]
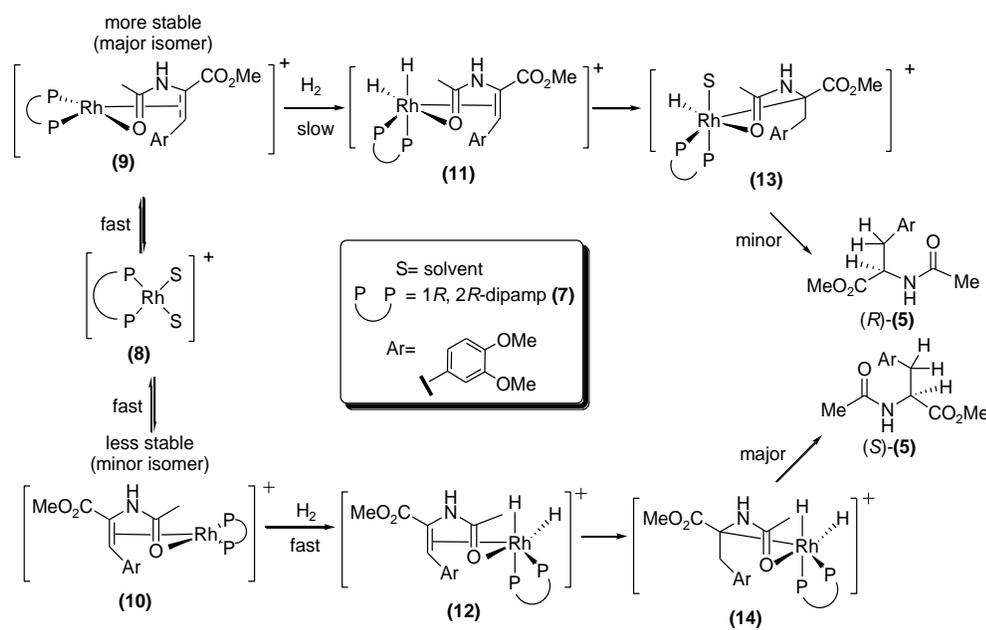
1). Chiral molecule initially binds to active rhodium catalyst this enables the simultaneous addition of hydrogen's to rhodium forming stable substrate complex.

2). The complex thus obtained reacts and H_2 is added to the double bond in the substrate. This is the hydrogenation stage, where a new chiral complex is formed from which the final chiral product is released.

(Thus from a substrate that is not chiral, chirality has been transferred from the chiral catalyst to the product.).

Figure 3. Mechanism of hydrogenation with Rh(I)dipamp.[10]

In 2001 another ¼ of a Noble prize (general hydrogenation) went to R. Noyori for the development of Ru–BINAP, this method demonstrated that high *e.e.* could be achieved if you maximize the energy difference between two complexes in the hydrogenation process. By using the transition metal ruthenium (Ru) a wide array of molecules were synthesised including (*R*)–1, 2–propanediol, which is used in the manufacture of the antibiotic levofloxacin. A stereoselective ketone reduction where the ester function is left intact is illustrated in **(Scheme 2)**.[11]–[14] The other ½ of the Noble Prize went to K. B. Sharpless for asymmetric oxidations **(Scheme 3)** and **(Figures 4, 5)**. [15], [16]
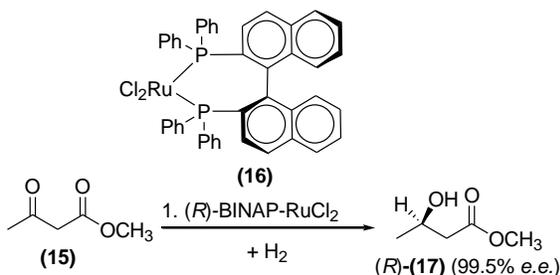
Scheme 2. The (*R*)–BINAP–Ru(II)–catalysed hydrogenation. [11–14]
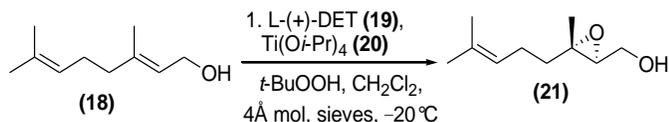
Scheme 3. Asymmetric synthesis using L–(+)–DET, Ti(O*i*–Pr)₄. [15, 16]
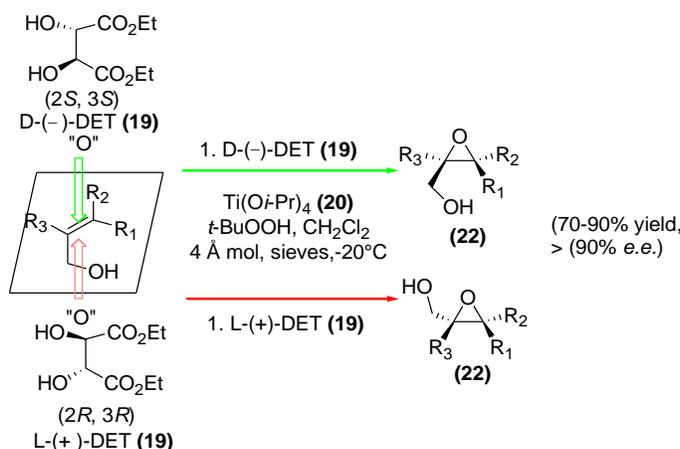
Figure 4. The predictive stereoselectivity of the Sharpless epoxidation is shown together with an example of its regioselectivity. [15], [16]

Co–ordination of the chiral ligand DET and the oxidant source *t*–BuOOH to the metal centre forms a *catalytically active species*. It is generally believed that this species is dimeric, i.e. two metal centres are bridged *via* two oxygen ligands giving the overall shape of two edge–fused octahedra. Co–ordination of the substrate can only occur in one orientation without causing severe steric interactions.

Figure 5. Theoretical model for catalytic species formed in the reaction. [15], [16]

1.1.4 Physical Properties and Structures of Metallocenes and their Derivatives.

Metallocene chemistry is interesting and important because of the opportunities that exist as a result of the number of electrons in the valence shell of transition metals. For example, early transition metal neutral metallocenes *i.e.* those that are electron deficient such as *bis*(cyclopentadienyl)titanium and *bis*(cyclopentadienyl)molybdenum (which exist as dimeric or polymeric structures) undergo addition reactions to the co–ordination sphere *e.g.* carbon monoxide (CO) and halogens (X) (ligands). However, late transition metal complexes which are electron rich undergo reactions which result in net loss of electrons in the co–ordination sphere of the transition metal. [17]

Ferrocene [*bis*(η⁵–cyclopentadienyl)iron(II)] **(25)** is an example of a fascinating sandwich metallocene and was first discovered accidentally by T. J. Kealy and P. L. Paulson in 1951 in a reaction between cyclopentadienyl magnesium bromide and ferric(II) chloride in the attempted synthesis of fulvalene. Ferrocene was reported as an orange powder with a melting point of 174–176°C and found to be insoluble in aqueous solvents (water, acidic and basic solutions).

The stability of this complex was attributed mostly to the aromatic character of the negatively charged cyclopentadienyl ligands. Only a few years later (1954) R. B. Woodward and G. Wilkinson determined the overall structure with the aid of infra red (IR), Nuclear Magnetic Resonance Spectroscopy (NMR) and X–ray crystallography. Noble prizes were awarded to E. O. Fisher and G. Wilkinson for their contribution in this field **(Figure 6)**. [9]
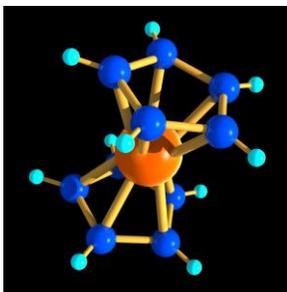
Figure 6. Computer simulation of ferrocene **(25)**. [9]

Several metallocenes have been synthesised from the first row transition metal series of the general formulae Cp_2M with the exception of titanocene as it adopts fulvalene–hydride structure. Cp ligands effectively stabilise metals in different d–electron counts and oxidation states (other then +2) **(Table 2) (Figure 7)**. [17]

Table 2. First row transition metal metallocenes. [17]

Metallocene	$\overset{V}{\text{(26)}}$	$\overset{Cr}{\text{(27)}}$	$\overset{Mn}{\text{(28)}}$	$\overset{Fe}{\text{(25)}}$	$\overset{Co}{\text{(29)}}$	$\overset{Ni}{\text{(30)}}$
Colour	Purple	Red	Amber	Orange	Purple	Green
m.p.	162	172	193	173	173	173
d electron count, unpaired electrons	15, (3)	16, (2)	17, (5/1 α)	18, (0)	19, (1)	20, (2)
M–C distance (Å)	2.28	2.17	2.38	2.06	2.12	2.20

α=exists in high and low spin states at thermal equilibrium

(31)
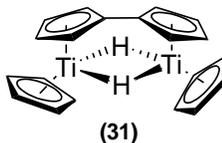
Figure 7. Titanocene, in a fulvalene–hydride structure. [17]

The bonding mode of Cp is described as being η^5(pentahapto), Cp ligands are understood to donate either 5 or 6 electrons to a transition metal **(Figure 8)**. The Molecular orbital (MO) diagrams **(Figure 9, 10)** illustrate that the lowest energy orbital a_1 does not have any preferable orbital overlap with the metal d–orbital. There is a little orbital interaction with the d_{z^2}, this is suggested to be because the ligand p–orbital is on the d_{z^2} conical nodal plane. There is a greater orbital overlap with the e_{1g} degenerate orbitals with the d_{xz} and d_{yz} orbitals on the metal orbitals, thus a strong π–bond is formed. Interaction between the e_{1u} and the metal p_x and p_y promotes stabilisation. The interaction between the metal

d_{xz-yz} and d_{xy} with the e_{2g} orbitals on the ligand is not sufficient and therefore these orbitals are considered to be non–bonding. [9]
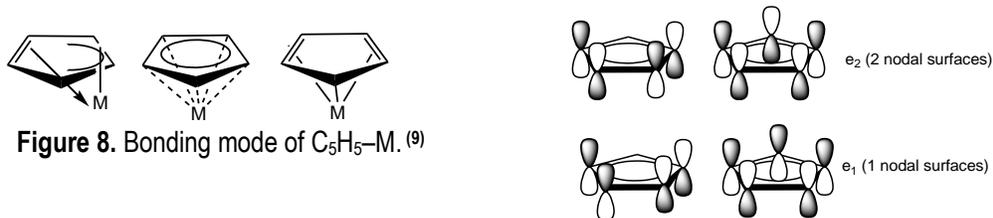
Figure 8. Bonding mode of C_5H_5–M. [9]

e_2 (2 nodal surfaces)

e_1 (1 nodal surfaces)

a_1 (0 nodal surfaces)
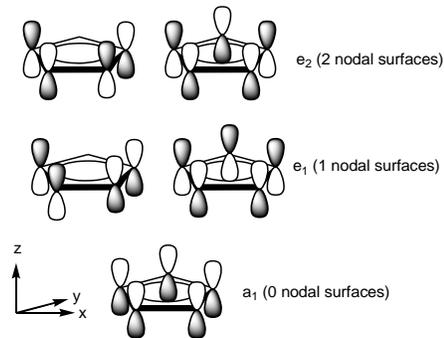
Figure 9. MO diagram of C_5H_5. [9]

The MO diagram for generic metallocenes, Cp_2M shows that the Cp orbitals fill the six lowest orbitals. The next five unoccupied MO's shown in the box have little or no bonding character, which explains the variety of d–electron counts
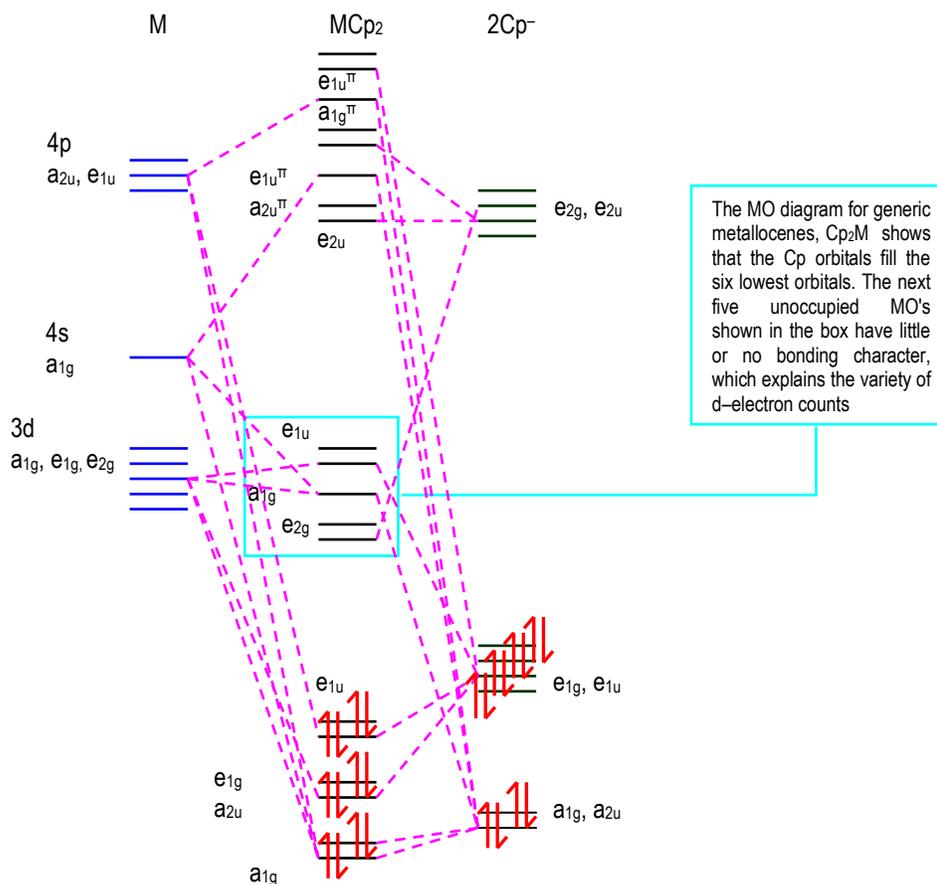
Figure 10. Molecular orbital diagram of organometallic sandwich complexes. [9]

1.2.0 Review of Methods for the Generation of Chiral Metallocene Derivatives.

The objective of this review is to detail the methodologies developed for the asymmetric synthesis of chiral metallocene complexes. The focus will be on the metallocene itself and will not consider the generation of appended stereogenic centres. The objective is not to consider in any detail the application of the complexes in organic synthesis. A number of excellent reviews have been published concerning the use of metallocenes as a platform for ligand synthesis and use in asymmetric catalysis. [18]

1.2.1 Resolution Techniques.

1.2.1.1   Enzyme Mediated Resolution.

The enzymes that are most used for the resolution of molecules are lipases and esterases. These enzymes usually catalyse the hydrolysis or formation of esters (hydrolases or acyl transfer catalysts) for example fatty acids are catalytically hydrolysed to glycerol. The main advantage of this type is they can withstand a wide range of substrates and are adaptable for use in organic solvents. Reactions in the acylation direction are done in the presence of acyl donors *e.g.* vinyl acetate, isopropenyl acetate as sources of the acyl group which gives unreactive acetone as a by-product. Lipases and esterases share a common mechanism that catalyses acyl transfer. The active site in the enzyme pocket involves a catalytic triad of imidazole from histidine, the hydroxy group from serine and carboxy group from aspartic acid. Initially interfacial activation phenomenon bridges them together allowing a conformational rearrangement of the lid, the oxyanion hole allows a constellation of properly located hydrogen bond donors to form which help stabilise the intermediate state **(Figure 11)**.
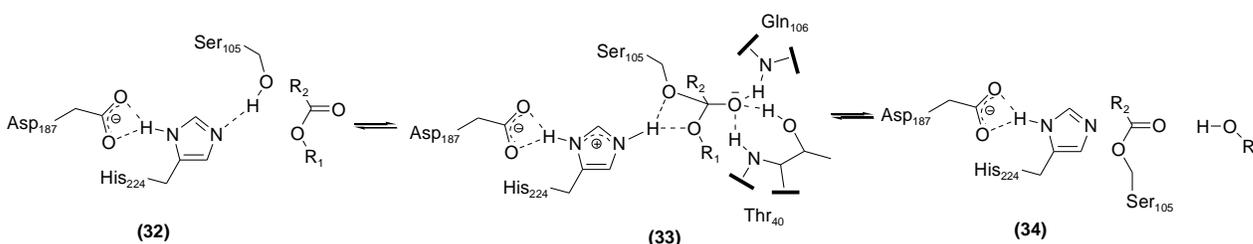
Figure 11. *Candida antarctica* lipase B mechanism of acyl transfer.

Enzymatic resolution techniques have been developed to resolve planar chiral (loss of a plane of symmetry) 1,2–disubstituted ferrocenes. This was prompted by the discovery of Y. Yamazaki and co workers that 1,2–*bis*(methylthiomethyl)ferrocene can be oxidised using *Corynebacterium equi* IFO 3730 to give **(36)** with a diastereomeric ratio of 4:1 **(Scheme 4)**. This reaction most importantly produced gave a specific planar chiral metallocene although the reaction was not very stereospecific with respect to chirality at sulphur. [19]
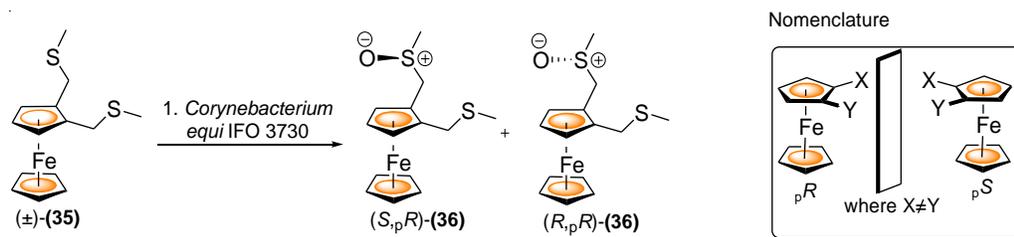
Scheme 4. Enzyme mediated desymmetrisation of 1,2–*bis*(methylthiomethyl)ferrocene (±)–**(35)**. [19]

One of the earliest reports of enzymatic resolution was of (±)–1,2–ferrocenophan–1–one **(37)** by hydrolysis to the enol acetate derivative (±)–**(38)** using commercial lipases. [19] When the enol acetate (±)–**(38)** was incubated with *Pseudomonas fluoescens* in a solution of phosphate buffer, the hydrolysis was reported to give optically active (+)–($_pR$)–**(37)** with a 24% *e.e.* and recovery of the enol acetate (+)–($_pS$)–**(38)** with greater than 99% enantiomeric excess **(Scheme 5)**. [19]
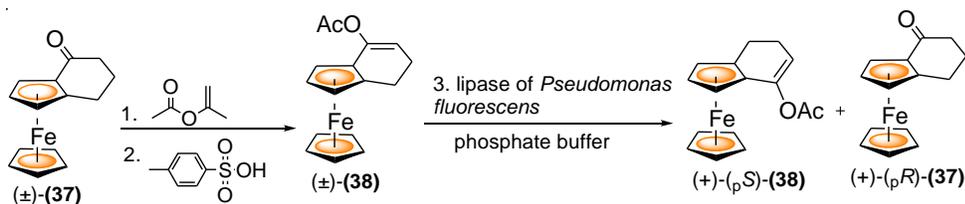
Scheme 5. Kinetic resolution of (±)–(1,2)ferrocenophan–1–one **(37)**.[19]

In another reaction it was reported that racemic acetate (±)–**(39)** could be treated with Lipase–MY (*Candida cylindracea*) in diisopropyl ether, allowing hydrolysis of (±)–**(39)** to give (+)–(*R*)–1–hydroxy–(*R*)–[4](1,2)–ferrocenophane (+)–(*R*,$_p$*R*)–**(40)** with a 99% enantiomeric excess with a 19% yield. The starting material (–)–(1*S*)–1–acetoxy–(*S*)–[4](1,2)ferrocenophanes (–)–(*S*,$_p$*S*)–**(38)** was recovered in 40% yield and found to have a 30% enantiomeric excess showing a selectivity factor of 400 **(Scheme 6)**. [19]
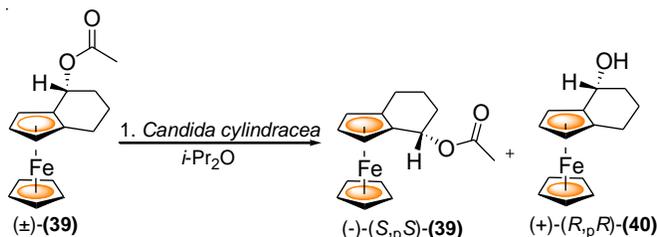
Scheme 6. Kinetic resolution of (±)–1–acetoxy–(1,2)ferrocenophane (±)–**(39)**. [19]

The enzyme catalysed transesterification of the racemates of 1–(1–hydroxyethyl)–2–(hydroxymethyl) ferrocene (HDMF) that exhibited both central and planar chirality was recently reported. [20] The substrates used for optical resolution was prepared from [(dimethylamino)methyl]ferrocene **(Scheme 7)**. The lipase which is derived from *Pseudomonas cepacia* was reported to be added in toluene and at regular intervals, the yields and enantiomeric excess was recorded by the removal of the enzyme. The enantiomeric excess (*e.e.*) of the products was determined by ¹H NMR spectral analysis in the presence of a chiral lanthanide shift reagent. Transesterification of the ferrocene diols was reported to be controlled initially by both the chemo differentiation between primary and secondary hydroxyl groups (the former reacting faster) and the enzymatic recognition of the planar chirality. The transesterification of 1–(1–hydroxyethyl)–2–(hydroxymethyl)ferrocene catalysed by *pseudomonas cepaaia* lipase using racemate A, showed at a short incubation time of 4 hours a 75% yield and 27% *e.e.* for the diol could be recovered with a monosubstituted ester in 25% yield and 79% *e.e.* However when the reaction time was increased to 36 hours the amount of diol recovered was 22% yield (>97% *e.e.*). Due to a longer incubation time, a monoester was also obtained in 55% yield with 10% *e.e.* as well as the diester in 18% yield (>97% *e.e.*). With respect to racemate B, a similar trend was observed, after 42 hours no diol was recovered however the monester was observed in 78% yield 27% *e.e.* and the diester in 17% and >95% *e.e.* **(Scheme 8)**.
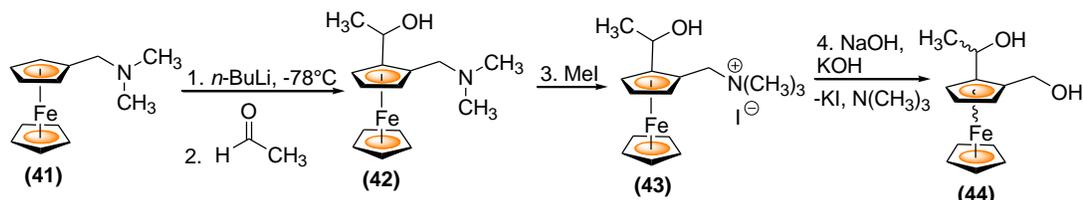
Scheme 7. Synthesis of racemates of 2–[(dimethylamino)methyl]–1(1–hydroxyethyl)ferrocene (HDMF) **(44)**.
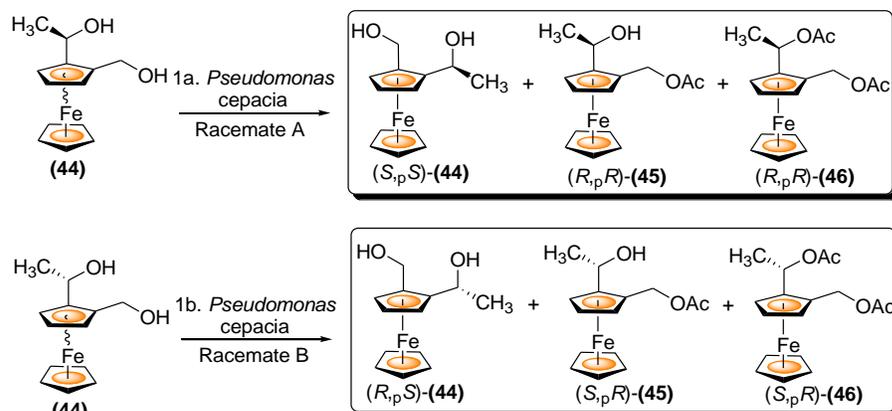
Scheme 8. Transesterification of ferrocene diols.

The enzymatic resolution of 2–hydroxymethylthioferrocene from the racemate using lipase catalysis was reported **(Scheme 9)**. [21] Initial attempts at esterification of 2–hydroxymethylthioferrocene (±)–**(47)** with vinyl acetate in toluene in the presence of different enzymes *i.e.* lipases from *Aspergillus niger, Rhizophus javanicus and Mucor javanicus* resulted in inactivity. However, lipases of *Mucor miehi* (immobilised, Liposzyme ® IM), *Candida Antarctica* (immobilised, Novozym ® 435), C. *cylindracea* and *Pseudomonas cepacia* was found to generate the ester (+)–($_p$S)–**(41)** in low enantiomeric excess when toluene is used as a solvent. However, when this solvent was replaced with *tert*–butyl methyl ether (*t*–BME) or diisopropyl ether (DIPE) better results were observed **(Table 3)**. Preprative esterification (conversion allowed to progress up to 50%) of (±)–**(47)** using Novozym ® 435 in DIPE gave (+)–**(48)** in 47% yield and 84% *e.e.* The planar chiral metallocene (–)–($_p$R)–**(47)** was recovered by cleaving the acetate using lithium aluminium hydride. It was reported that if esterification was allowed to proceed up to a conversion value of 60% (*ca.* 4 hours), the enantiomeric excess for the unreacted alcohol goes up to 95%.
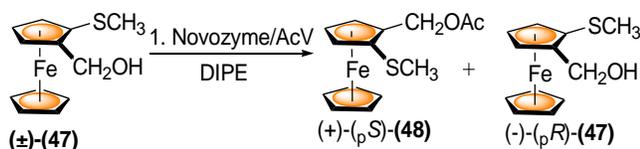
Scheme 9. Lipase mediated resolution of racemic 2–hydroxymethyl–1–methylthioferrocene. [21]

The absolute configuration of (–)–($_p$R)–**(47)** was determined by chemical correlation. This was done by determining the absolute configuration of ester (+)–($_p$S)–**(48)** in a reaction with dimethyl amine in aqueous methanol to give compound (–)–($_p$S)–**(49)**, subsequent conversion to 1,2,3–ferocenyl derivative (–)–($_p$S)–**(49)** with an *ortho* directing of amino group gave (–)–($_p$S)–**(50)**. Reductive removal (Raney nickel) of the methionine group gave (–)–($_p$R)–**(51) (Scheme 10)**. [21]

Table 3. Acetylation of 2–hydroxymethyl–1–methylthioferrocene promoted by different lipases. [21]

Lipase from	Time, (min)	Conv., (%)	e.e., ester [a]	S	stereopreference	e.e., (%) alcohol
Mucor miehei (Lipozyme® IM)	25	46	81	20	($_p$R)	69
Candida Antarctica (Novazym® 435)	55	32	90	30	($_p$R)	48
Candida cylindracea	20	36	76	11	($_p$R)	42
Pseudomonas cepacia	300	20	33	2	($_p$S)	22

Experimental conditions; diisopropyl ether as solvent; substrate 10 mg/mL; lipase 20 mg/mL; vinyl acetate 10 μL/mL (10 equiv.). [a]. Determined after reductive deacylation with $LiAlH_4$ by ^1H NMR in the presence of $Eu(hfc)_3$.
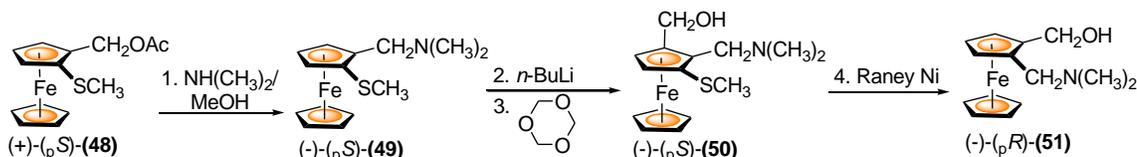
Scheme 10. Determination of absolute configuration of (+)–($_p$S)–**(48)** by correlation with (–)–($_p$R)–**(51)**. [21]

In a paper published in 2008, [22] the effect additives had on transesterification in the enzymatic resolution of (±)–**(47)** using the enzyme *Candida rugosa* lipase was reported. It was evident from their investigation that using molecular sieves increased the rate of reaction and also improved the selectivity factor. While the addition of water, ethylene glycol or DMSO (hydrophilic solvents) or too many molecular sieves resulted in no reaction. Using DMF was found to have little effect on enantiomeric excess. Using commercially available *o*–(4–chlorobenzoyl)hydroquinine gave a selectivity factor of 143 when conversion reached 53% using vinyl acetate in toluene. The additive Cinchonidine was found to give a selectivity value of 103 after 24 hours in toluene using isopropenyl acetate as the acylating agent. Cinchonine was also effective as with this additive a higher selectivity factor was observed *i.e.* S value of 100 **(Figure 12)**. Using organic bases such as triethylamine or pyridine did not have much effect on selectivity. Using a stronger base such as DMAP resulted in complete inhibition of the reaction. The additive 1,4–diazabicyclo[2.2.2]octane (DABCO) gave an unexpected result as it increased enantioselectivity of the reaction. However it was proposed to be as a result of playing an active role in the catalytic cycle *i.e.* by allowing the substrate to become more accessible to the active enzyme receptor site. [22]

R$_1$=OH, R$_2$= H Cinchonidine **(53)**
R$_1$=H, R$_2$= OH Cinchonine **(54)**
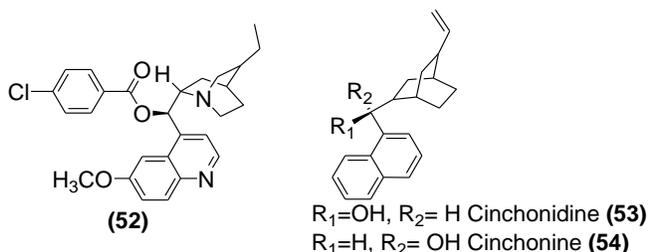
Figure 12. Examples of additives used for the kinetic resolution (±)–**(47)**. [22]

Enzymatic resolution was used in the synthesis of aminoalcohol derivatives of ferrocene to make useful catalysts for asymmetric synthesis. [23] Using ferrocene cyanohydrin allowed access to novel β–aminoalcohols and diamines. Lipase catalysed acylation of (±)–**(55)** resulted in the acetate (+)–($_p$S)–**(56)** (84% *e.e.*) **(Scheme 11)**. This process involved

adding (±)–**(55)** (1.60 g) to Pseudomonas *cepacia* lipase (1.60 g, Amano) and shaking the mixture in deionised water followed by pouring the mixture into a solution of vinyl acetate (35 mL). Filtration of this mixture followed by evaporation of the filtrate and then chromatography of the crude mixture using 15% deactivated Al_2O_3 with a 1:1 CH_2Cl_2/petroleum ether (40–60°C) gave a product which was recrystallised to give (+)–($_p$S)–**(56)** >95% *e.e.* Isolation of the substrate cyanohydrin was reported to be abandoned due to instability when using chromatographic techniques *i.e.* silica, alumina resulting in the undesired synthesis of ferrocenecarboxaldehyde. [23]
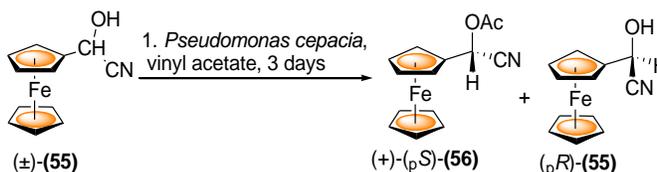
Scheme 11. Lipase catalysed acylation of (±)–**(55)**. [23]

Candida antarctica (Novozym® 435) was recently used in an enzymatic resolution of 2–hydroxymethyl–1–iodoferrocene (±)–**(57)**. [24] In a reaction of (±)–**(57)** with vinyl acetate in dichloromethane was found to give a *2S*–stereopreference with the level of selectivity equal to 67 for preparative use. Large scale reactions were reported to be feasible with substrate conversions of up to 52% which was found to give 96% *e.e.* for (+)–(R,$_p$R)–**(57)** and 89% *e.e.* for (−)–(S,$_p$S)–**(58)** **(Scheme 12)**.
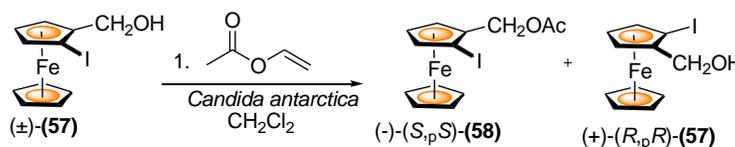
Scheme 12. Kinetic resolution of 2–hydroxymethyl–1–iodoferrocene (*rac*)–(±)–**(50)**. [24]

In summary, kinetic resolution initially suffered the problem of reversibility in ester formation with chiral alcohols which resulted in decreased optical purity. This problem was solved by using irreversible acyl transfer reagents such as the enol acetates vinyl acetate or isopropenyl acetate. The main advantage of using enzyme mediated resolution is the fact that only mild reaction conditions are needed. Esterases have been found to enable desymmetrisation by acylation or hydrolysis to give chiral alcohols or esters. However, these enzymes are less stereoselective. For example; the active sites of pig liver esterase (PLE) have polar pockets and hydrophobic pockets of varying size, the relative size of these regions give rise to the fit of the substrate *e.g.* alkyl and aryl groups fit either in big or small hydrophobic pockets based on their size. Polar pockets can for instance accommodate moderately polar groups such as esters or hydroxy, carbonyl groups, lone pair of electrons and exclude non polar groups. Depending on where these regions are in the active site and their relative size orientate only one of the substrates *i.e.* one planar chiral metallocene to undergo a stereoselective reaction. Lipases which are a sub class of esterases have found to be more effective as they are more selective to the substrate. The dominant factors that were found to give rise to enantioselectivity were better discrimination between binding to hydrophobic and polar pockets. For example, the most common lipase used is porcine pancreatic lipase (PPL) which works best above the solubility limit of a hydrophobic substrate. When reactions are done at the critical micellor concentration the enzyme pocket was found to be more responsive to a conformational change. Lipases were found to work better in solvents such as acetone, diethyl ester and DMSO.

1.2.1.2   Diastereoselective Resolution.

Crystallisation driven resolution (or classical resolution) involves resolution *via* diastereomeric salt formation. Since the discovery by L. Pasteur in 1853, this technique has been used immensely despite the drawbacks *i.e.* a maximum yield of 50% can be obtained. Recent developments have enabled up to 100% yield to be obtained *i.e. via* crystallisation and *in situ* racemisation. In 1962 this technique was used to resolve planar chiral 1,1'–dimethylferrocene–3–carboxylic acid **(59)** using the alkaloid cinchonidine. [25] The quinidine salt was reported to be crystallised from aqueous ethanol as a monohydrate with crystals held together by a system of hydrogen bonds. The absolute stereochemistry was determined using X–ray crystallography. This method was understood to be effective because it confines the dimensions of the interior pore of the salt by allowing only a limited number of orientations a bulky reactant can assume as its docking vector thus encouraging a stereospecific reaction, enantioselectively. The alkaloids found to be effective for the formation of salts with 1,1'–dimethylferrocene–3–carboxylic acid **(59)** were cinchonidine, quinine, strychnine, cinchonine, brucine and quinidine. The alkaloid quinidine was found to give the highest amount of recovered 1,1'–dimethylferrocene–3–carboxylic acid as a crystallised salt **(Figure 13)**. [26]
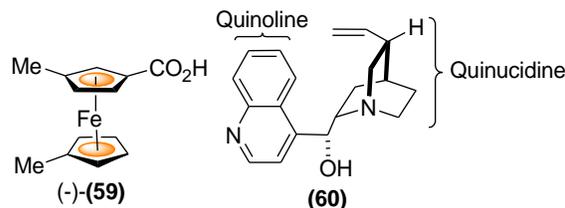
Figure 13. Structures of (–)–1,1'–dimethylferrocene–3–carboxylic acid **(59)** and alkaloid quinidine. [26]

The diamine (*R,R*)–1,2–di(*N*–methylamino)cyclohexane which possesses a C_2–axis of symmetry has been used to resolve racemic aldehyde *rac*–**(61)**. Treatment of *rac*–**(61)** with 1.05 equivalents of (*R,R*)–1,2–di(*N*–methylamino)cyclohexane **(63)** at room temperature gave a 1:1 mixture of diastereoisomers of aminals (*R,R*,$_p$*S*)–**(62)** and (*R,R*,$_p$*R*)–**(62) (Scheme 13)** which were separated in quantitative yields by silica gel column chromatography. Using a two–phase solvent system of CH_2Cl_2/HCl (aq) allowed cleavage which resulted in enantiomerically pure aldehydes ($_p$*S*)–**(61)** and ($_p$*R*)–**(61)** >97% yield. The amine auxiliary used was reported to be recovered in 89% yield after extraction with CH_2Cl_2 followed by sublimation. X–ray crystallography was used to determine the structure and elucidate the absolute configuration. [27]
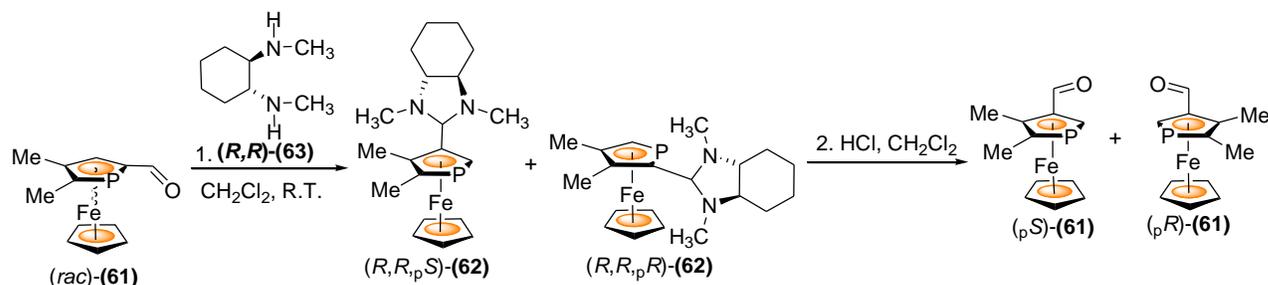
Scheme 13. Synthetic strategy used to obtain enantiomerically pure planar chiral phosphaferrocenes. [27]

1.2.1.3 Non–enzymatic Kinetic Resolution.

C. J. Richards in 2001 and T. Hayashi in 2002 reported procedures for the preparation of ferrocenophanes by Ru– or Mo–catalysed metathesis reaction on 1,1'–diallylferrocenes. They realised that metathesis could take place diastereoselectively to give either *meso*–or *dl*–bridged metallocenes depending on the reaction conditions employed. [28]

In 2006, the first effective non–enzymatic kinetic resolution of planar chiral ferrocenes was reported **(Scheme 14)**. [29] Using the Sharpless methodology for catalytic asymmetric dihydroxylation (AD) on racemic 2–substituted 1– ethenylferrocenes **(64a–d)**. It was evident that kinetic resolution was predominantly affected by the 2–substituent of ferrocenylethenes. For example, bulkier substituents like (CON(i–Pr)$_2$ and 4,4–dimethyl–1,3–oxazolin–2–yl gave high enantioselectivity factors as opposed to less bulkier ones like TMS or I.

The enantioselectivity factor K_s was found to range from 20 to 62 [for (DHQD)$_2$PYR ligands], and from 5 to 27 [for (DHQ)$_2$PYR ligands]. The stereochemistry of the reaction was predicted using a mnemonic device for AD, and preferred transition states *i.e.* π–stacking interactions in the stabilisation of the transition state (TS) result in vinylferrocene having a co–planar geometry. **Figure 14** illustrates how the presence of a bulky substituent adjacent to the vinyl group destabilises one of the two limiting planar conformations. Thus, one of the enantiomers of 2–substituted 1–vinylferrocene approaches only one face of the olefin and is more reactive compared to the other. For example, in the case of the ($_pR$)–enantiomer of a 2–substituted 1–vinylferrocene, dihydroxylation takes place on the *si*–face of the alkene, thus making the (DHQD)$_2$PYR–catalysed reaction faster than the (DHQ)$_2$PYR–catalysed reaction. [29]

Using this concept it was also stated the reverse would happen *i.e.* fast dihydroxylation of the *re*–face with (DHQ)$_2$PYR ligand, and slow reaction for the (DHQD)$_2$PYR ligand on the ($_pS$)–enantiomer **(Scheme 15)**. The catalytic kinetic resolution (KR) of racemic 2–substituted 1–vinylferrocenes was found to agree with the mnemonic of the reaction *i.e.* (DHQD)$_2$PYR ligand is more selective, for a given olefin, compared to (DHQ)$_2$PYR. In the case of (DHQD)$_2$PYR ligand, the enantioselectivity factor of the resolution decreases along the following sequence: **(64a>d)**. [29]

In the case of (DHQ)$_2$PYR ligand, the enantioselectivity decreases in the order of **(64b)>(64a)>(64d)>(64c)**. This was postulated to be as a result of the quasi–enantiomeric relationship that exists in these types of ligands. With respect to the trend, it was suggested that ferrocenylethenes with the bulky substituents **(64a)**, **(64b)** are better substrates for the K_R as opposed to the less bulky ones **(64c), (64d)**. Also (DHQD)$_2$PYR ligands tend to react preferentially with ($_pR$) enantiomers of planar–chiral ferrocenylethenes **(64a–d)**, thus resulting in ($S_{C,p}R$) diols and unreacted alkenes of major ($_pS$) stereochemistry. In the case of (DHQ)$_2$PYR ligands, the opposite is observed. The asymmetric dihydroxylation of (+)–($_pS$)–**(64c)** with (DQH)$_2$PYR ligand is shown in **Scheme 15**. [29], [30]
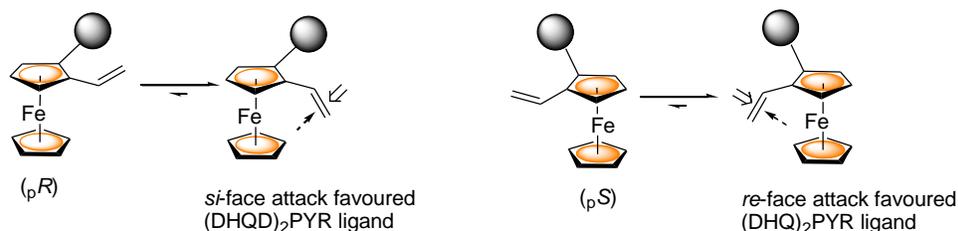
Figure 14. Predicted enantiomer and face–selectivity in the Sharpless asymmetric dihydroxylation of 2–substituted–1–vinylferrocenes. [29], [30]

(a) R=CON(*i*-Pr)$_2$, **(b)** 4, 4'-dimethyl-1, 3-oxazloin-2-yl, **(c)** TMS, **(d)**; I.
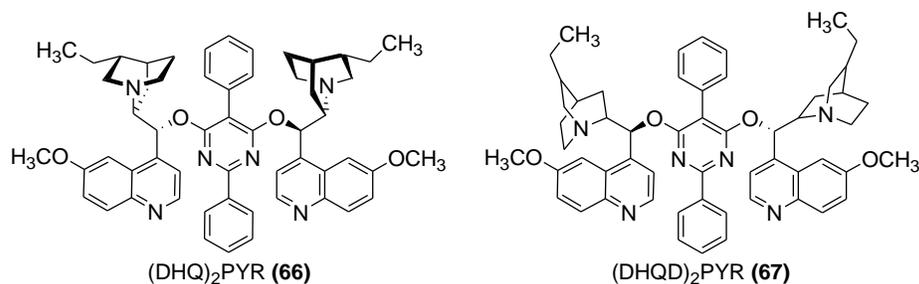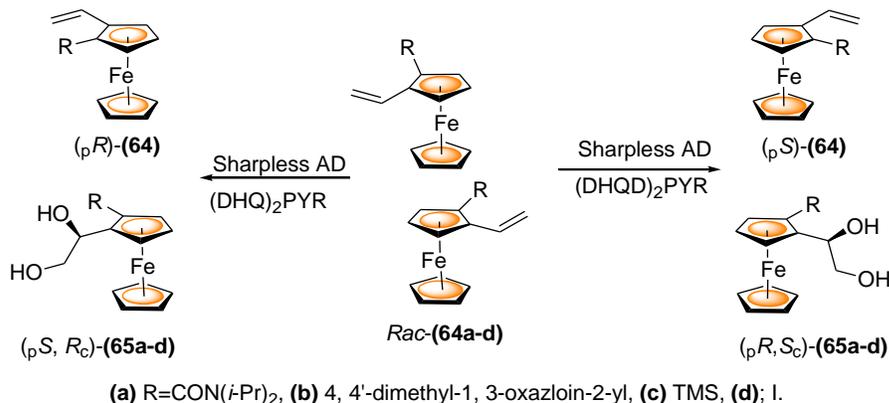
Scheme 14. Kinetic resolution of 2–substituted–1–vinylferrocenes by asymmetric dihydroxylation using phthalazine based ligands. [29], [30]

A notable resolution was using the alkene (±)–**(64a)** with the ligand (DHQD)$_2$PYR (5 mol%) for 10 mins gave (+)–($_p$S)–**(64a)** in 16% yield with an enantiomeric ratio of 96:4 as the recovered alkene and (+)–(S_C,$_p$R)–**(65a)** in 44% yield with an enantiomeric ratio of 95:5. The selectivity factor was 62.3 which was the highest reported. With respect to the ligand (DHQD)$_2$PYR (5 mol%) using the alkene (±)–**(64c)** for 25 mins gave (+)–($_p$S)–**(64c)** in 23% yield and 15:85 enantiomeric ratio for the recovered alkene. The diol product (–)–($S_{C,p}$R)–**(64c)** was obtained in 47% yield and an enantiomeric ratio of 94:6. The highest selectivity factor was reported using this method which gave 43.3. The conditions and reagents found to be effective were 1.5 mol equiv. K$_3$[Fe(CN)$_6$] (re–oxidises the osmium), 1.5 mol equivs. K$_2$CO$_3$ (increases rate of reaction) ligand–K$_2$OsO$_2$(OH)$_4$ ratio=1.3:1, 0.5 mmol alkene in 30 mL 1:1 CH$_3$CN–H$_2$O, room temperature. Osmium tetroxide (OsO$_4$) is the active catalyst in the reaction.
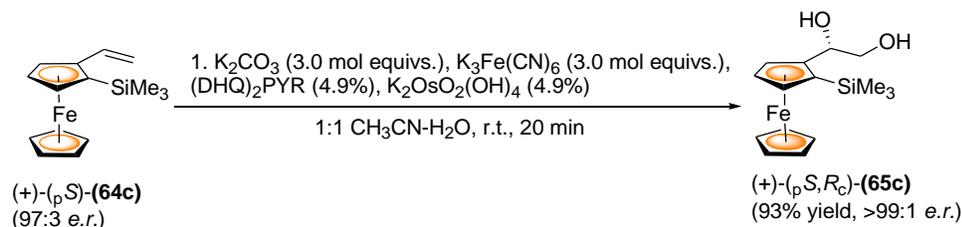
Scheme 15. Asymmetric dihydroxylation of (+)–($_p$S)–**(64c)** with the "matched" (DQH)$_2$PYR ligand. [29], [30]

Also in 2006, [31] the kinetic resolution of optically active planar chiral 1,1–diarylferrocene derivatives using molybdenum–catalysed asymmetric ring closing metathesis (ARCM) with exceptional enantioselectivity (**Scheme 16**, **Table 4**). ARCM kinetic resolution was found to be predominantly influenced by the substituents present on the allylic group in the monosubstituted cyclopentadienyl moiety. The enantioselectivity was improved significantly when a η^5–C$_5$H$_4$–methallyl group was present in ferrocene substrates. The mechanism for selectivity is illustrated in **Figure 15**.
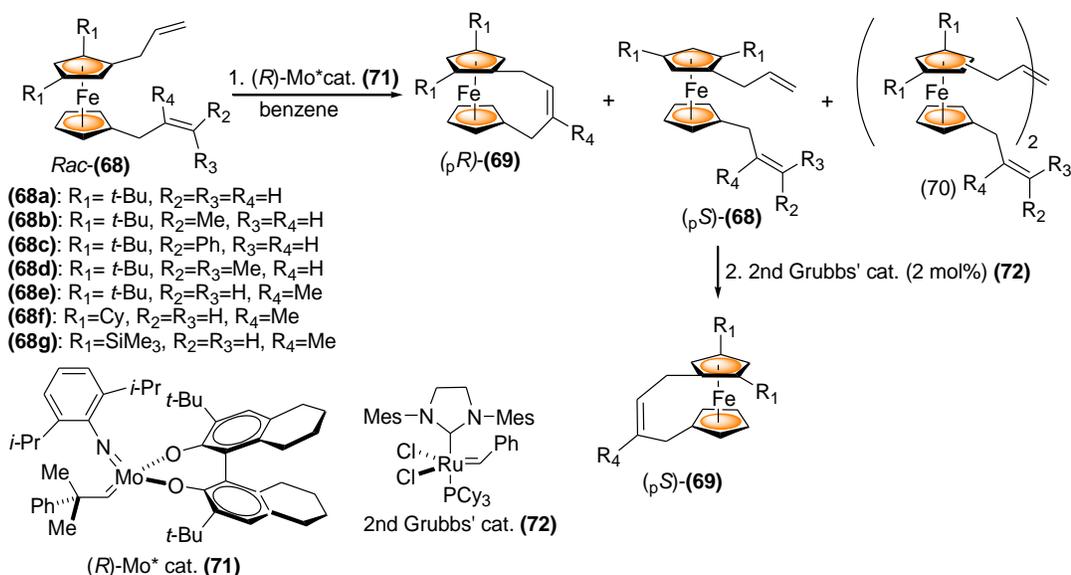
Scheme 16. ARCM kinetic resolution of planar chiral ferrocenes and metathesis catalysts. [31]

Table 4. Molybdenum–catalysed asymmetric RCM kinetic resolution of planar–chiral ferrocenes. [31] [a]

Entry	Substrate **(68)** (mol/L) [b], [c]	Mo* cat. (%)	Conditions	Yields (%) **(69)/(68)/(70)**	% e.e. [d] **(69)/(68)**	K$_s$ [e]
1	**(68a)** (0.1)	5	23°C, 15 min	73/26/trace	<1/2	1.03
2	**(68b)** (0.1)	5	23°C, 1h	44/49/trace	12/9	1.4
3	**(68c)** (0.01)	10	80°C, 24h	26/53/16	66/29	6.4
4	**(68d)** (0.01)	5	70°C, 24h	0/54/38	–/7	
5	**(68e)** (0.1)	5	23°C, 4h	23/30/47	>99.5/78	>500
6	**(68e)** (0.005)	10	50°C, 24h	46/47/3	96/95	183
7	**(68f)** (0.005)	10	50°C, 24h	43/41/12	82/83	26
8	**(68g)** (0.005)	10	50°C, 24h	45/52/trace	97/81	165

[a]. The reaction was carried out in benzene in the presence of the molybdenum catalyst (R)–Mo*. [b]. Initial concentration of the substrate. [c]. Isolated yields of the products **(69)** and **(70)** and the recovered substrate **(68)**. [d]. Enantiomeric excess of the recovered **(68)** was determined after converting them into **(69)** by a reaction with the second generation Grubbs' catalyst. [e]. Calculated based on a first–order equation.
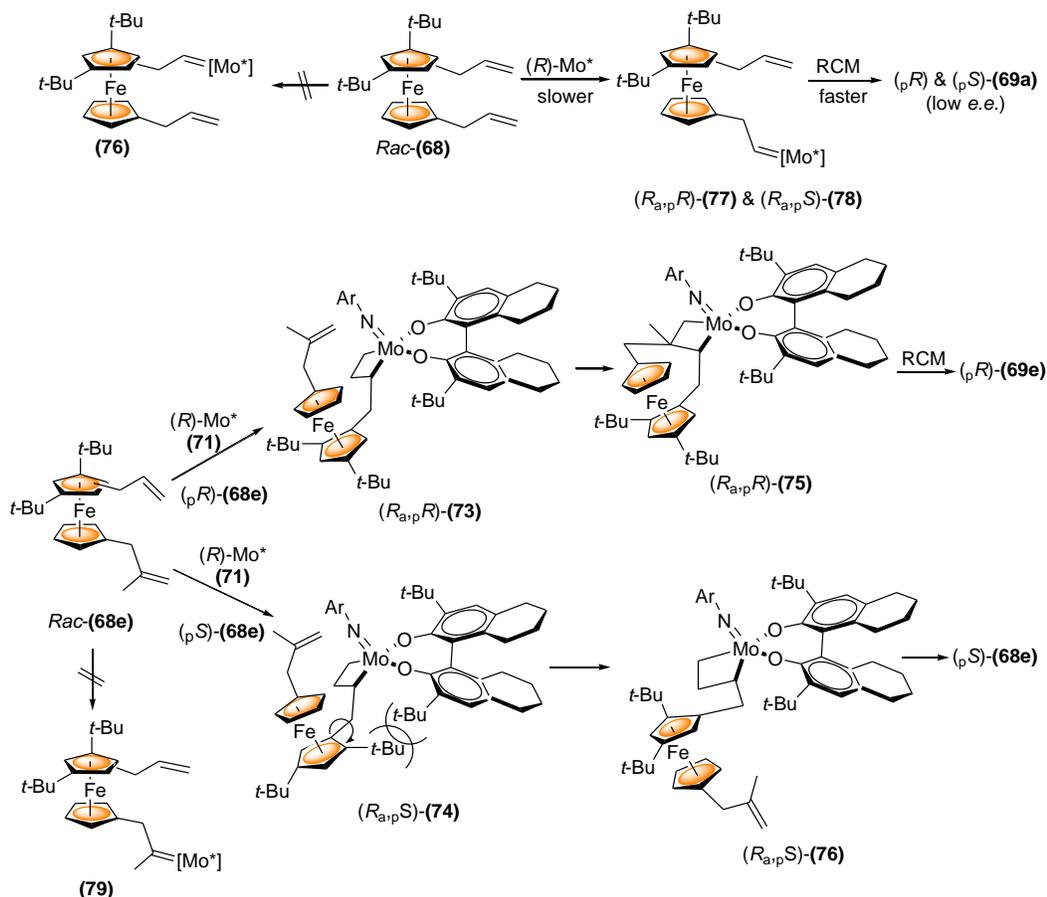
Figure 15. Plausible stereochemical pathways of the Mo–Catalysed ARCM kinetic resolution. [(31)]

A. Moyano and co–workers in 2009 reported an organocatalytic kinetic resolution which involved a proline–catalysed aldol reaction of racemic 2–(2'–pyrimidyl)ferrocenecarbaldehyde with acetone in DMSO at room temperature. They report the reaction gave a selectivity factor in kinetic resolution for ($_pR$)–**(80)** of 9.2 **(Scheme 17, Table 5)**. They justified the stereochemistry and proposed a model that was similar to the already well established proline–catalysed aldol reaction. They postulated that the L–proline–catalysed aldol reaction between a ketone and a 2–substituted ferrocenecarbaldehyde gives four diastereomeric transition states. The first and second transition states show ferrocene to be equatorial and in a chair like conformation which is known to be the most stable. Steric interaction in the third and fourth transition state is understood to have a destabilising effect **(Figure 16)**. [(32), (33), (34)]
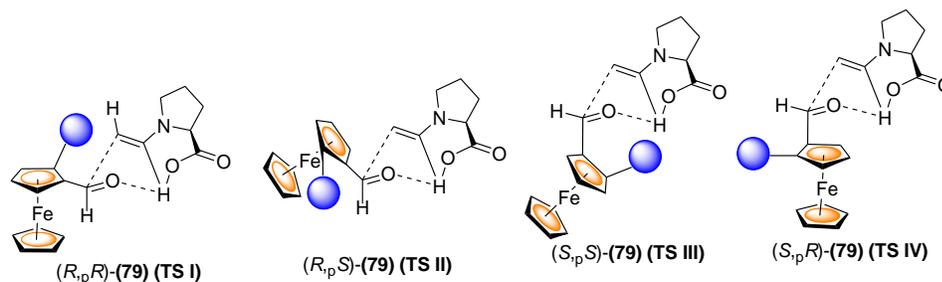
Figure 16. Diastereomeric transition states for the L–proline–catalysed intermolecular aldol reaction for a 2–substituted ferrocenecarbaldehyde. [(32), (33), (34)]
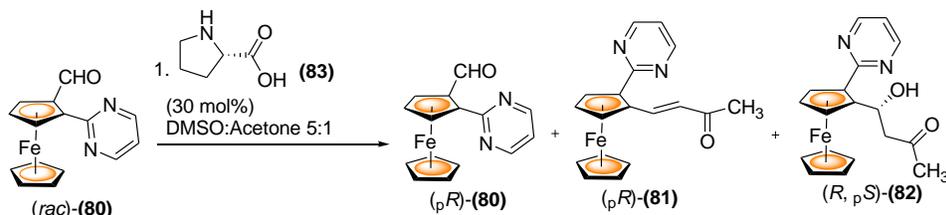
Scheme 17. Kinetic resolution of planar–chiral ferrocenecarbaldehyde **(80)** by asymmetric organocatalytic aldol reaction with acetone. [32], [33], [34]

Table 5. L–Proline–catalysed aldol reaction of racemic aldehyde **(80)** with acetone at different conversions. [32], [33], [34]

Entry	% Conversion	(80) (% Yield, [a] % e.e.)	(81) (% Yield, [a] % e.e.[b])	(82) (% Yield, [a] % e.e.[b])
1	30	70, 33	15, 62	15, 57
2	35	65, 42	13, 55	22, 52
3	45	55, 53	24, 50	21, 48
4	56	44, 73	30, 40	26, 38
5	63	37, 78	41, 34	21, 36
6	95	5, ndc	65, 2	31, 8

[a]. Yield of isolated product after chromatographic purification. [b]. By HPLC (Chiralcel OD column). [c]. Not determined.

The non enzymatic kinetic resolution of (*rac*)–2–oxazolin–2–ylferrocenylphosphine **(89)** was reported using cyclic selenoxide (R_a)–**(87)** and (R_a)–**(88)** which were synthesised from axially chiral C_2–symmetric cyclic selenides (R_a)–**(85)**, (R_a)–**(86)** by oxidising them with *m*–chloroperbenzoic acid with potassium carbonate **(Scheme 18).** With respect to (R_a)–**(87)** when this reagent was stirred at 20°C overnight in carbon tetrachloride and in the presence of phenol moderate enantioselectivity of up to 13% *e.e.* in the case of the phosphine oxide and up to 29% *e.e.* for the phosphine were reported with a selectivity factor of 2.3. Using (R_a)–**(88)** on (*rac*)–2–oxazolin–2–ylferrocenylphosphine **(89)** had no effect on enantioinduction **(Scheme 19)**. [35], [36]
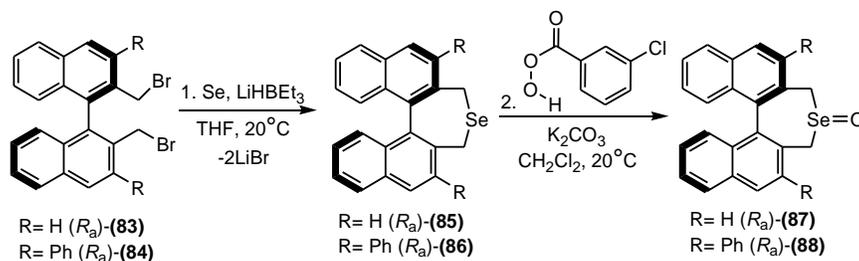
Scheme 18. Synthesis of cyclic selenoxide (R_a)–**(87)** and (R_a)–**(88)**. [35], [36]
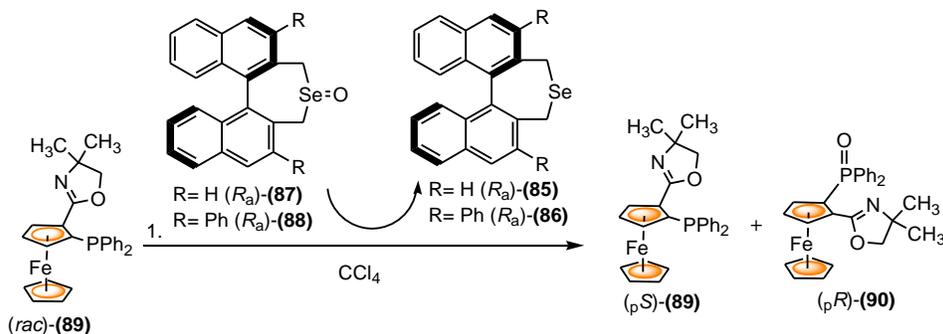
Scheme 19. Kinetic resolution of (*rac*)–2–oxazolin–2–ylferrocenylphosphine **(89)**. [35], [36]

1.3   Diastereoselective Complexation.

Planar chiral metallocenes can be synthesised *via* a diastereoselective complexation, this involves coordinating a chiral molecule to a metal source. For example, S. Takahashi and co workers reported the isolation of **(94)**, **(95)** and **(96)** using this methodology. [37] The precursor synthesis was reported to involve using a catalytic amount of toluene–*p*–sulfonic acid (*p*–TsOH), **(91)** and (–)–menthol **(92)** then heating to reflux in xylene. An alcohol exchange reaction was reported to give (–)–menthyl ester (*S,R,R*)–**(93) (Scheme 20)**. Using (*S,R,R*)–**(93)** and reacting it with FeCl$_2$ this gave the desired planar chiral diastereoisomers. 'H NMR and chiral HPLC analysis was reported to be used to identify all three isomers **(94)**, **(95)** and **(96) (Scheme 20)**. Asymmetric induction by this chiral (–)–menthyl group was reported to allow the separation of the mixture of diastereoisomers by preparative HPLC using hexane/ benzene as the elutant. [37] The planar chiral metallocenes synthesised via diastereoselective complexation were obtained in a combined yield of 67% with the ratio determined by HPLC. The isolated yields of the compounds were lower, **(94)** gave 4% yield, **(95)** gave 28% yield and **(96)** gave 21% yield.
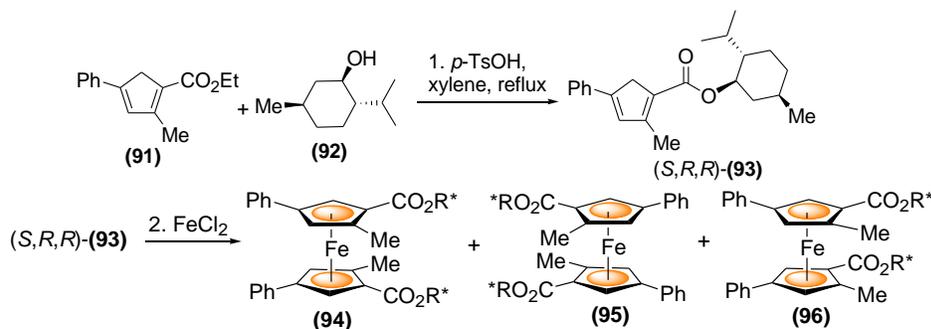
Scheme 20. Synthesis of planar chiral metallocenes *via* diastereoselective complexation.

The first synthesis of optically active planar chiral cyclobutadiene complexes using trisubstituted cyclopentadiene was reported. [38] By initially functionalising the ester linkage with a chiral (–)–menthyl group. This chiral source was then used to make the precursor cyclooctadiene complexes **(98)**, **(99)**. Chiral HPLC was reported to be ineffective at separating the diastereoisomers with the exception of **(98a)** and **(99a)** *i.e.* when R$_1$= Ph was successful and not when R$_1$= Me **(Scheme 21)**. Both diastereoisomers were partially purified using silica gel column chromatography and used in the next step of the sequence to make cyclobutadiene complexes **(Table 6)**. Both diastereoisomers of the cyclobutadiene complexes were isolated by silica gel column chromatography. Using **(101a)** in a reaction with methyl lithium (+)–($_p$S)–**(103)** was synthesised as a planar chiral metallocene **(Scheme 22)**. [38]
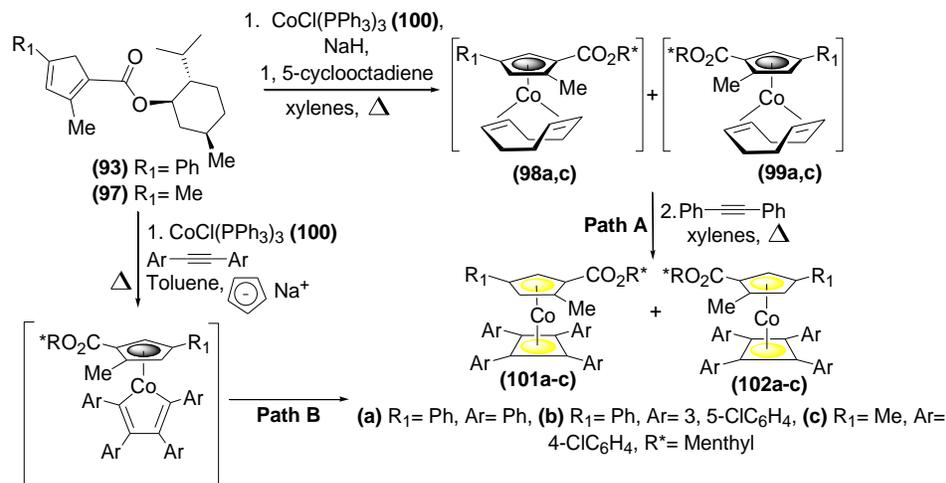
Scheme 21. Planar chiral cyclobutadiene complexes using trisubstituted cyclopentadiene. [38]

Table 6. Synthesis of optically active cyclobutadiene complexes. [38]

Entry	Method	Product	Ar	Yield (%)[a]	Optical rotation
1	A	(101a) (102a)	Ph	28 36	+46 −5.6
2	B	(101a) (102a)	Ph	27 35	− −
3	B	(101b) (102b)	3, 5–$Me_2C_6H_4$	29 32	+93 −32
4	B	(101c) (102c)	4–ClC_6H_4	16 18	+7 −2

[a] Isolated yields.

Scheme 22. Enantiopure synthesis of (+)–($_p$S)–(91). [38]

Another example of a complexation reaction was reported using enantiomerically enriched (*R*)–1–butyn–3–ol **(104)** and reacted it with two equivalents of *bis*(trimethylsilyl)acetylene **(105)** and one equivalent of η^5–(C_5H_5)Co(CO)$_2$ **(106)** which subsequently gave them ($R_{C,p}S$)–**(107)** with an enantiomeric excess of 62% and ($R_{C,p}R$)–**(107)** with an enantiomeric excess of 60%, with an overall yield of 34% **(Scheme 23)**. [34] Following on from this interesting result the same research group later explored thermally induced diastereoisomerisation. When an enriched sample of the planar chiral metallocene ($R_{C,p}R$)–**(107)** 62% *e.e.* was heated to 571°C a mixture in the ratio of 65.6:34.4 was observed in 56% *e.e.* for ($R_{C,p}S$)–**(107)** and 58% *e.e.* for ($R_{C,p}R$)–**(107).** Thus demonstrating diastereoracemisation was taking place at the cobalt centre. [39], [40]
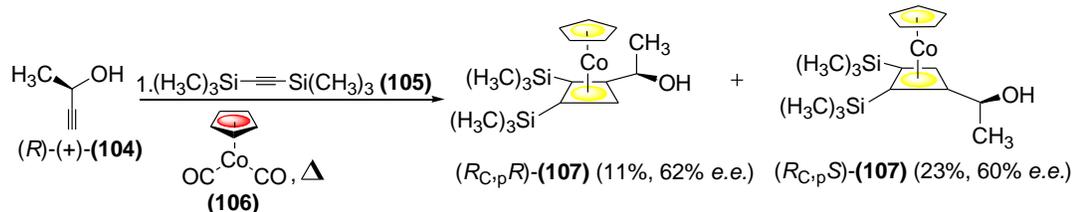
Scheme 23. Synthesis of diastereoisomers using optically active (*R*)–(+)–**(104).** [39], [40]

The pinene–fused cyclopentadiene (PCpH) ligand **(108)** was reported by C. Ganter and co–workers to be react with Fe(CO)₅. [41] The coordination chemistry was found to be under thermodynamic control which results in the metal fragment coordinating exclusively to the sterically less hindered *exo*–side, exemplified in the dinuclear complex **(110)**. With 2 equivalents of *t*–butylphosphole **(111)** in xylene, reactants were refluxed to give **(112)** in 65% yield **(Scheme 24)**.

When PCp–phosphaferrocene **(112)** was subjected to the Vilsmeier–Haack formylation reaction it gave a 70% yield of the diastereomeric aldehydes **(113)** in the ratio of 2:1. Attempted separation of the diastereomers using both chromatography and or recrystallisation was found to be ineffective. Thus the aldehyde complexes **(113)** were transformed into aminals (*R*,*R*,ₚ*S*)–**(114)** and (*R*,*R*,ₚ*R*)–**(114)** by reacting them with enantiopure (*R*,*R*)–1,2–di(*N*–methylamino)cyclohexane and then were isolated using silica gel column chromatography **(Scheme 24)**. [41]
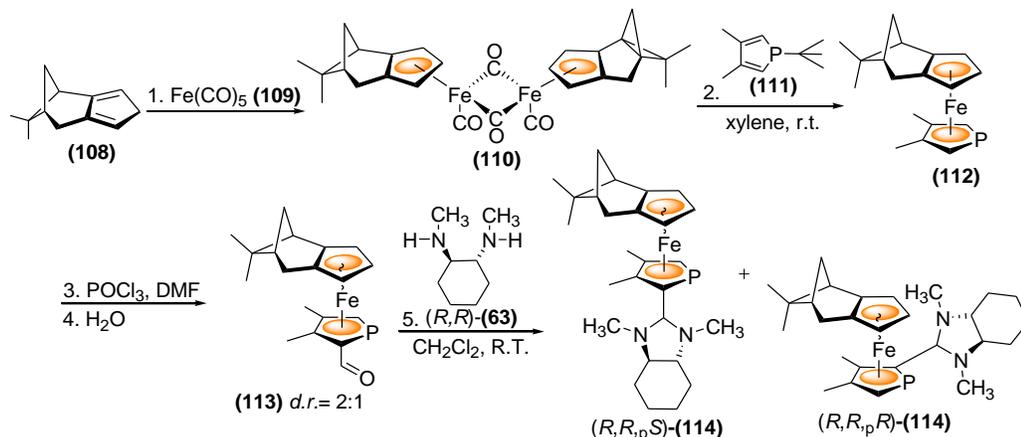
Scheme 24. Synthesis of phosphaferrocenes containing the chiral pinene fused cyclopentadienyl ligand. [41]

1.4 Diastereoselective Methods using Non–covalently Attached Stoiciometric Chiral Source.

In 1995 N. S. Simpkins reported an enantioselective *ortho*–lithiation using a non covalently attached chiral source. The chiral lithium amide (*R*,*R*)–**(116)** is an example of a reagent that was successfully used as a chiral base in the synthesis of (ₚ*R*)–**(117)** achieving 95% yield and 54% enantiomeric excess after being quenched with the electrophile trimethylsilyl chloride (TMSCl) **(Scheme 25)**. [42]
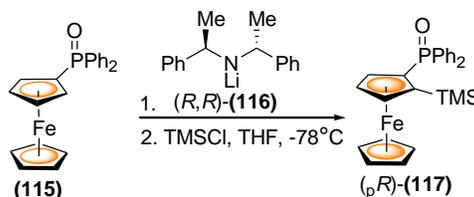
Scheme 25. Asymmetric metallation of ferrocene complex by chiral lithium amide base (*R*,*R*)–**(116)**. [42]

When the unsymmetrical amine **(119)** was used on **(118)** and subsequently quenched with diphenylphosphino chloride (Ph$_2$PCl) it gave planar chiral phosphine ($_p$R)–**(120)** with 62% *e.e.* and 25% yield. When the electrophile was dimethylformamide (DMF) it gave a similar yield for ($_p$R)–**(121)** but with an enantiomeric excess of 80% **(Scheme 26)**.[43]
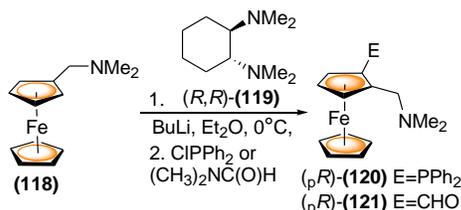
Scheme 26. Application of stoiciometric chiral source (*R,R*)–**(119)**. [43]

In 1996 a direct and highly enantioselective synthesis of planar chiral ferrocenes was reported using the alkaloid (–)–sparteine **(123)** in a (–)–sparteine–mediated *ortho* metallation or lithiation (DoM). **Scheme 27, Table 7** illustrates the diverse nature of this chemistry in terms of functionality. Moreover in **Scheme 28** reduction (BH$_3$/THF) of **(124d)** to give **(125)**. The metallation of **(124a)** using achiral reaction conditions (1.2 equiv of *n*–BuLi/THF or *s*–BuLi/Et$_2$O) and benzophenone quench furnished **(126)**. Directed *ortho* metallation cross coupling was demonstrated in a Suzuki procedure with (2,4–dimethoxyphenyl)–boronic acid to afford **(127)**, although low yields were observed the enantiomeric excess remained the same. The following year, the (–)–sparteine methodology was extended to the diamido ferrocene complex **(128)**, this generated **(130)** in 58% yield and 98.5% enantiomeric excess, by changing to *s*–BuLi the consequences were a synthesis of the *meso*–product **(130)** in 85% yield. The problem of the *meso* compound by–product was overcome by subjecting **(129)** to the same reaction conditions initially used **(Scheme 29)**. [44]
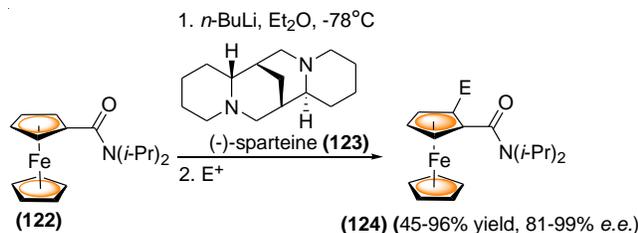
Scheme 27. Application of stoiciometric chiral source (–)–sparteine **(124)**. [44]

Table 7. *n*–BuLi/(–)–sparteine–induced metallation of *N,N*–diisopropyl ferrocenecarboxamide. **(44)**

E+ (a)	E	Product	Yield%, (b)	e.e.,%
TMSCl	TMS	(pS)–**(124a)**	96	98
MeI	Me	(pR)–**(124b)**	91	94
Et₂CO	Et₂C(OH)	(pR)–**(124c)**	45	99
Ph₂CO	Ph₂C(OH)	(pR)–**(124d)**	91	99
ClCH₂OCH₃	CH₂OCH₃	(pS)–**(124e)**	62	81
I₂	I	(pS)–**(124f)**	85	96
(PhS)₂	PhS	(pS)–**(124g)**	90	98 (c)
(PhSe)₂	PhSe	(pS)–**(124h)**	92	93 (c)
Ph₂PCl	Ph₂P	(pR)–**(124i)**	82	90 (c)
B(OMe)₃	B(OH)₂	(pS)–**(124j)**	89	85

(a). 2.2 equiv of *n*–BuLi/(–)–sparteine was used with the exception of E+) TMSCl, Et₂CO, and Ph₂CO (1.2 equiv of *n*–BuLi/(–)–sparteine). (b). All yields refer to isolated and purified materials. (c). Compounds **(124g–i)** underwent slow racemisation at room temperature. Therefore, *e.e.* determination was carried out immediately after purification.

Scheme 28. Enantioselective synthesis of metallocenes. **(44)**

Scheme 29. Enantioselective synthesis of metallocenes using (–)–sparteine **(123)**. **(44)**

1.5   Auxiliary Methods.

The pioneering work of I. K. Ugi and co workers on C_2–functionalisation of enantiopure *N,N*–dimethyl–1–ferrocenylethylamine **(Scheme 30)** which introduces planar chirality into the ferrocene backbone by a diastereoselective *ortho* lithiation with an appropriate chiral *ortho* directing group and subsequent trapping with an electrophile has been adopted as the standard protocol for preparation of compounds of this nature. [45]
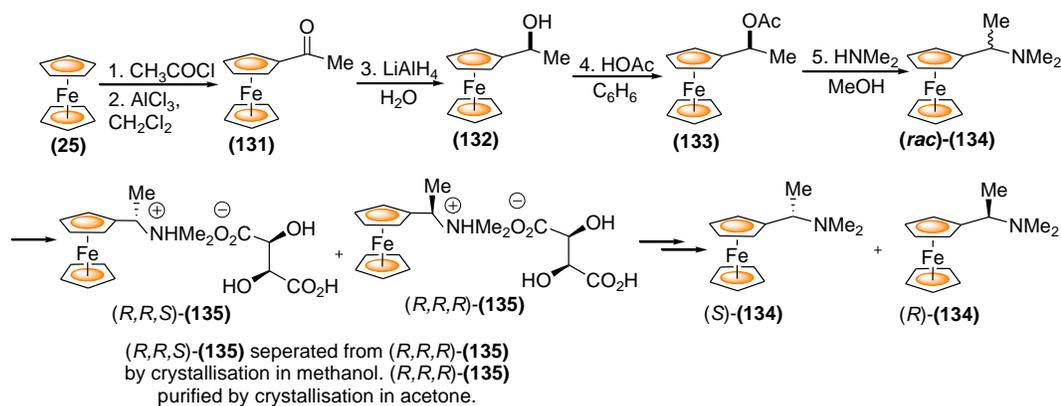
Scheme 30. Synthesis of both enantiomers of *N,N*–dimethylaminoferrocene (Ugi–amine) **(134).**

M. Hayashi and K. Kumada in 1974 utilised the highly diastereoselective lithiation of 1–*(N,N*–dimethylamino)ethylferrocene **(134) (Figure 17)** followed by the introduction of the electrophile *i.e.* chlorodiphenylphosphine to prepare one of the first examples of enantiopure planar chiral ferrocenyl phosphine (R,$_p$S)–**(137)** 'PPFA' which showed good reactivity in asymmetric catalysis. This was a major scientific breakthrough as a series of high profile chiral ferrocene P,P–ligands and mixed donor P,N–ligands were developed as a consequence *e.g.* (R,$_p$S)–**(138)** 'Josiphos', [46] (R,$_p$S)–**(139)** 'Taniaphos', [47] **(140)** Walphos, [48] and **(141)** Bophoz [49] are to name but a few **(Figure 18)** which were similar to chiral P,P–ligands *e.g.* (S,S)–**(145)** BPPM [50] (K. J. Achiwa), (S,S)–**(146)** CHIRAPHOS [51] (B. J. Bosnich), **(147)** DuPHOS, [52] (M. J. Burk), **(148)** BICP, [53] (Q. Zhang), (R)–**(149)** PHANEPHOS, [54] (K. Rossen), **(150)** PENNPHOS, [55] (X. Zhang), (R)–**(153)** BIPHEMP, [56] (P. Schönholzer), (R)–**(154)** P–PHOS, [57] (A. C. S. Chan), (R)–**(151)** SEGPHOS, [58] (K. Mikami) and (S,S)–**(152)** TANGPHOS, [59] (X. Zhang) developed from after (S,S)–**(155)** DIOP, [60] by H. B. Kagan in 1972 **(Figure 19)**.
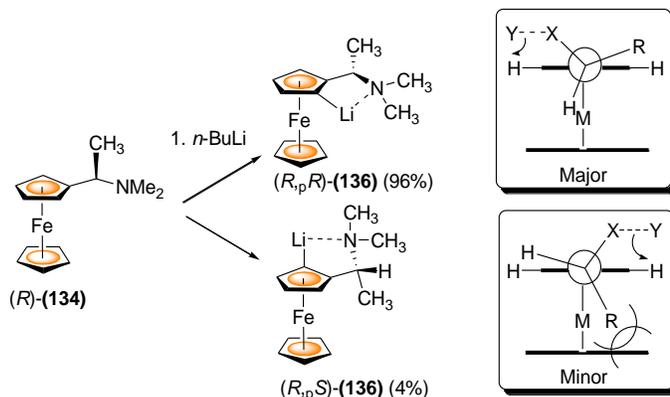
Figure 17. Substituent containing a suitably located donor atom on one of the Cp rings directs lithiation to the adjacent position. [46]
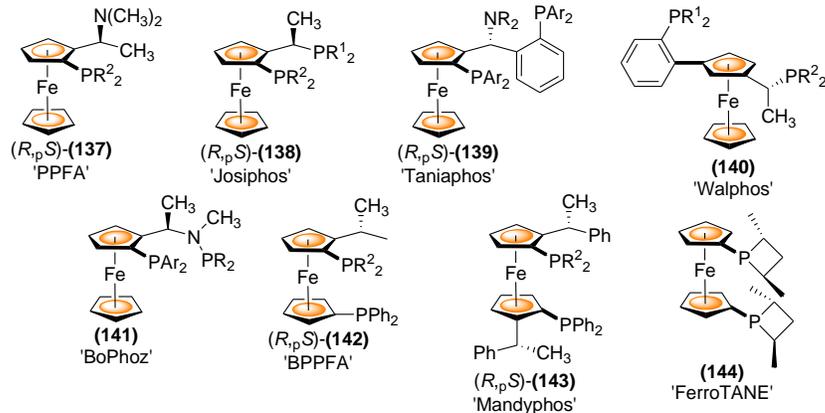
Figure 18. Examples of well known chiral ferrocenyl phosphine ligands.
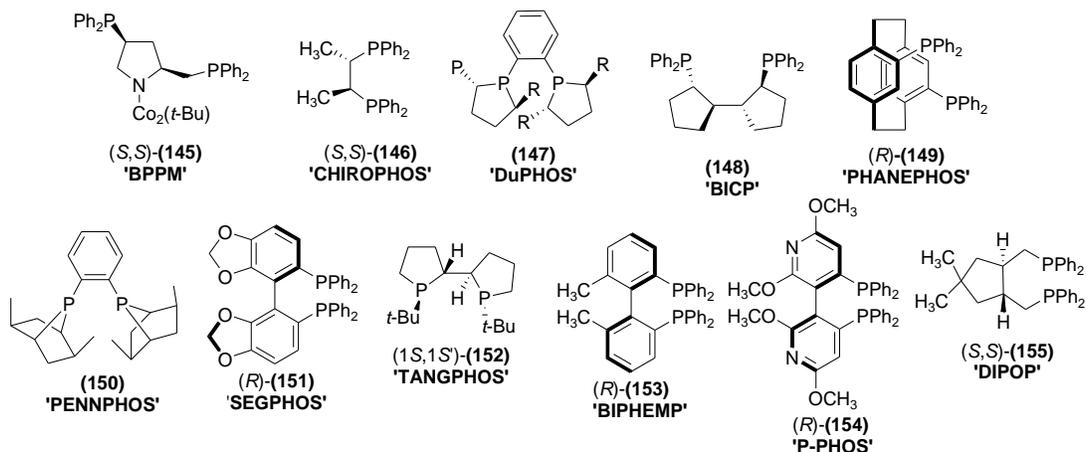
Figure 19. Examples of chiral phosphine ligands.

1.6   Nitrogen Substitution in 1–*(N,N*–dimethylamino)ethylferrocene.

The 'Ugi amine' (*R*)–**(134)** was shown to be an effective compound for the enantiopure synthesis of planar chiral metallocenes *via* nitrogen substitution. Diastereoselective lithiation followed by addition of trimethylsilyl chloride gave (*R*,ₚ*S*)–**(156).** Treatment with methyl iodide resulted in a stereospecific substitution to take place. This phenomenon was reported to be accessible as a result of retention of configuration by the α–carbenium ion intermediate **(158)**. The mechanism was rationalised with the bond being α– to the ring which can be considered as a partially formed double bond which prevents restricting rotation. Retention of configuration is made possible as the nucleophile in this sodium methoxide approaches from the same direction as the leaving group exits **(Scheme 31)**. [61]
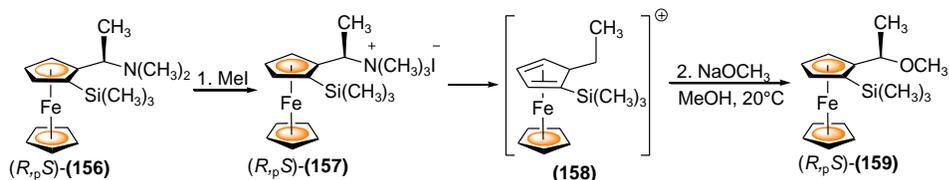
Scheme 31. Stereospecific nitrogen substitution reaction. [61]

1.6.1 Synthetic Routes to 1,2–Unsymmetrical Ferrocenes *via* Nitrogen/Phosphorus Exchange.

Nitrogen/phosphorus exchange as illustrated in **Scheme 32** was shown to allow the synthesis of a diverse range of planar chiral metallocenes with varying electronic and steric properties. For example, by heating at 80°C in glacial acetic acid in the presence of a secondary phosphine important ligands such as the aforementioned $(R,_pS)$–**(138)** 'Josiphos' can be synthesised using this method. [18d], [63]
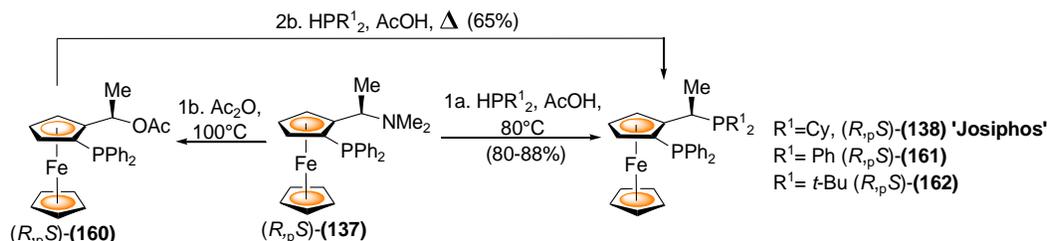
Scheme 32. Synthesis of ferrocenylphosphines by separate introduction of two phosphorus groups. [18d], [63]

Modification of the amine with a phosphorus group that is not a diarylphosphine was demonstrated using 9–phospha–9H–bicyclo[3.3.1]nonane (phobane) with the principle benefit being that it is sterically less bulky. This reagent was reported to be made by reacting 1,5–cyclooctadiene with phosphine (PH_3) generating a 2:1 mixture of major [3.3.1] and minor [4.2.1] isomers. **Scheme 33** illustrates the synthesis of the 'Phobyphos' ligand **(167)** and also a chiral tridentate *bis*ferrocenyl ligand **(166).** This ligand proved that the amine group can be substituted with a cyclohexylphosphine group and still maintain retention in configuration. [64]
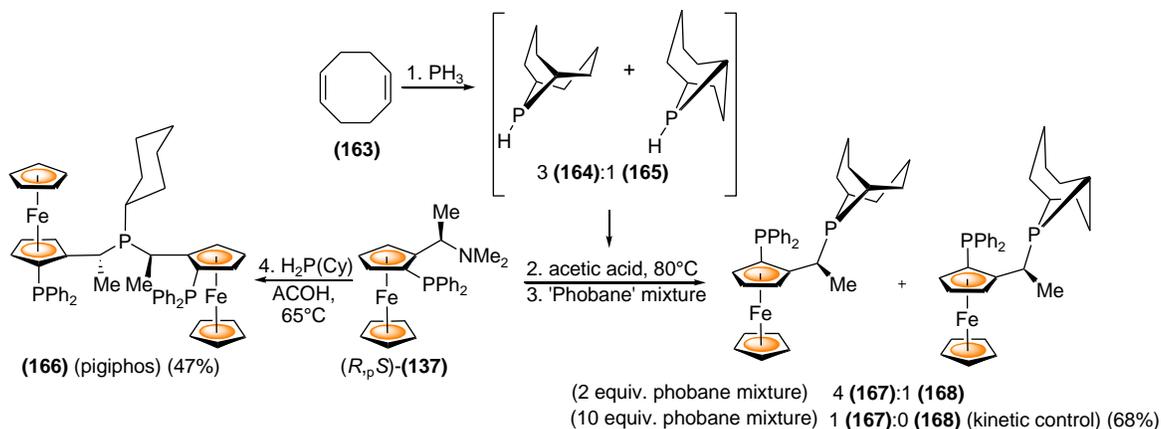
Scheme 33. Examples of 1,2–unsymmetrical ferrocene ligands, derived from amine–phosphorus exchange. [64]

Another recent example of N,P exchange was reported. [65] In an unprecedented synthesis of new tridentate phosphine ligands 'P3Chir'. The interesting feature of the complexes that were described was the planar chirality of the ferrocenyl moiety was combined with the central chirality of both phosphorus and carbon stereocenters. Using either $(R,_pS)$–**(137)** {or $(S,_pR)$–**(137)**} **(**PPFA**)** and reacting it with racemic $C_6H_5P(H)CH_2CH_2P(O)(C_6H_5)_2$ in the presence of acetic acid resulted in a 1:1 mixture of diastereomers of **(172)** having opposite absolute configuration at phosphorus (step c). Treating this mixture with borane dimethyl sulphide and then purifying it was found to give $(R,_pS,S_P)$–**(174)** and

$(R,_pS,R_P)$–**(175)**. Reduction of the two stereoisomers afforded $(R,_pS,S_P)$–**(179)** and $(R,_pS,R_P)$–**(179)** (**Scheme 34**, step f and g). [65]
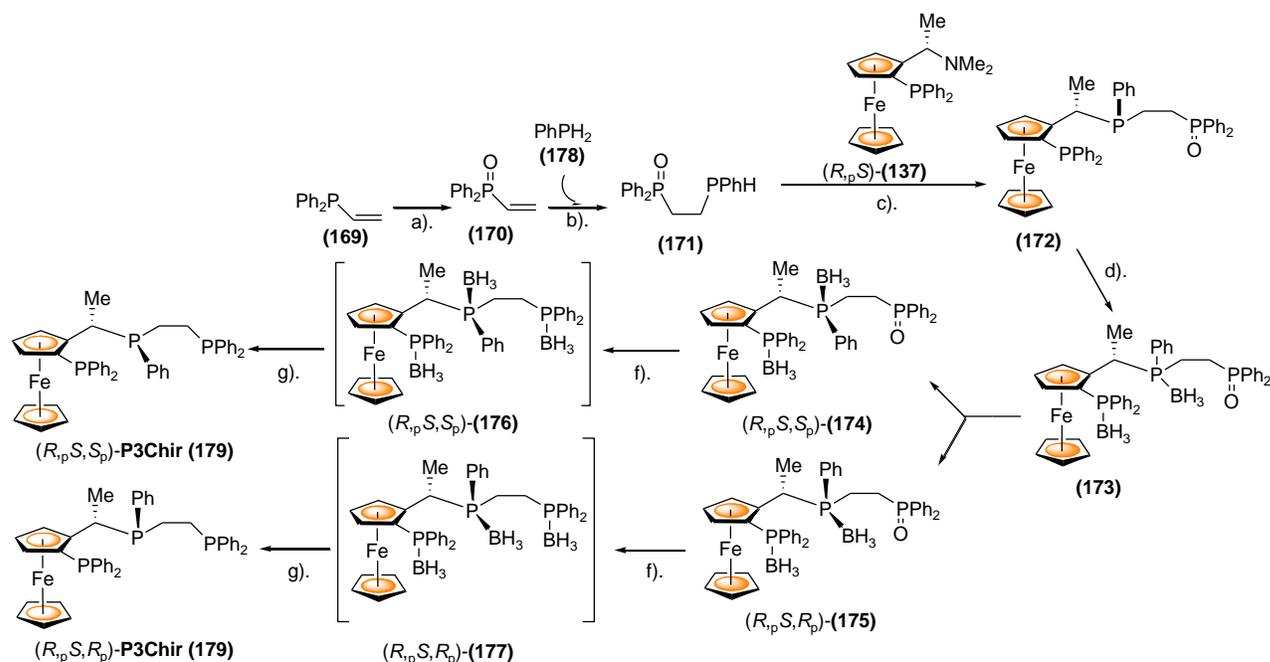
Scheme 34. Synthesis of $(R,_pS,S_P)$–**(179)**–P3Chir and $(R,_pS,R_P)$–**(179)**–P3Chir. *Reagents and conditions*: a). H_2O_2, $CHCl_3$; b). t–BuO⁻K⁺, THF, reflux; c). AcOH, 75°C; d). $BH_3 \cdot (CH_3)_2S$, THF; e). flash chromatography; f). $CeCl_3$, $NaBH_4$, $LiAlH_4$, THF; g). morpholine, 70°C. [65]

1.6.2 Synthetic Routes to 1,2–Unsymmetrical Ferrocenes *via* Nitrogen/Nitrogen Exchange.

Replacement of the amine group with a pyrazole ring at the α–stereogenic centre in a nucleophilic substitution reaction was reported to give phosphinopyrazole ferrocene and ruthenocene ligands **(Scheme 35)**, **(Scheme 36)**. Depending on the substituents used impressive yields of between (38–67%) have been obtained for ligands of this nature. The element of tuning the ligand was made simpler by changing the R–R_3 (pyrazole) and Ar substituents *i.e.* when both the N–ligand was a good σ–donor and the P–ligand was a good π–acceptor. For example, when a 3,5–dimethylpyrazolyl fragment is incorporated in the design it results in increased electronic asymmetry (the pyrazoyl nitrogen acts as a good σ–donor with virtually no π–acceptor character, with the phosphorus ligand acting as a good π–acceptor). [66]
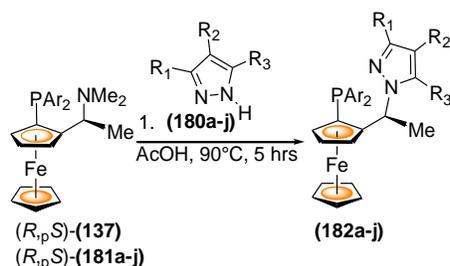
	(180a–j)			
Ligand	R_1	R_2	R_3	Ar
(R,$_p$$S$)–(182a)	Me	H	Me	Ph
(R,$_p$$S$)–(182b)	CF$_3$	H	CF$_3$	Ph
(R,$_p$$S$)–(182c)	Me	Me	Me	Ph
(R,$_p$$S$)–(182d)	CF$_3$	H	Me	Ph
(R,$_p$$S$)–(182e)	i–Pr	H	i–Pr	Ph
(R,$_p$$S$)–(182f)	Me	Br	Me	Ph
(R,$_p$$S$)–(182g)	H	H	H	Ph
(R,$_p$$S$)–(182h)	Ph	H	Me	Ph
(R,$_p$$S$)–(182i)	Me	H	Me	4–CF$_3$C$_6$H$_4$
(R,$_p$$S$)–(182j)	Me	H	Me	4–MeOC$_6$H$_4$

Scheme 35. Synthesis of pyrazolyl–containing ferrocenyl ligands. [66]
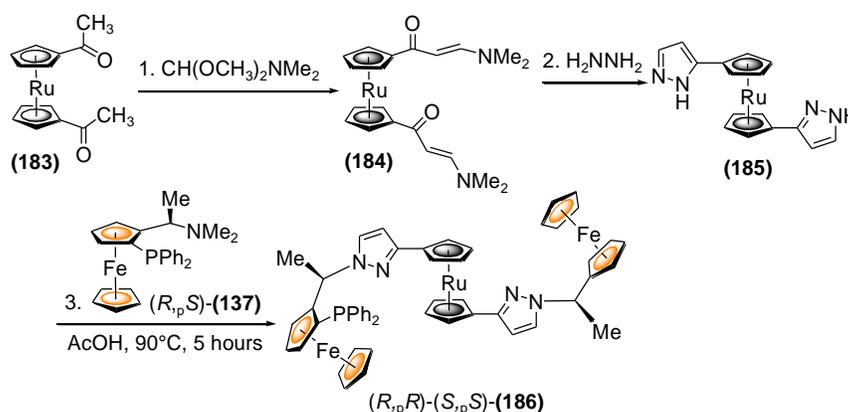
Scheme 36. Synthesis of a *bis*(ferrocenylphosphine/pyrazole) (R,$_p$$R$)–($S$,$_p$$S$)–(186) ligand. [67], [68]

Chiral ferrocenylphosphines containing an imino group such as (S,$_p$$R$)–(189) were reported to be synthesised in good yields from (S)–N–alkylidene–1–[($_p$$R$)–2–diphenylphosphinoferrocenyl]ethylamines (S,$_p$$R$)–(188). This method involved a condensation reaction between (S)–1–[($_p$$R$)–2–diphenylphosphinoferrocenyl]ethylamine with arylcarboxaldehyde **(Scheme 37)**. [69]
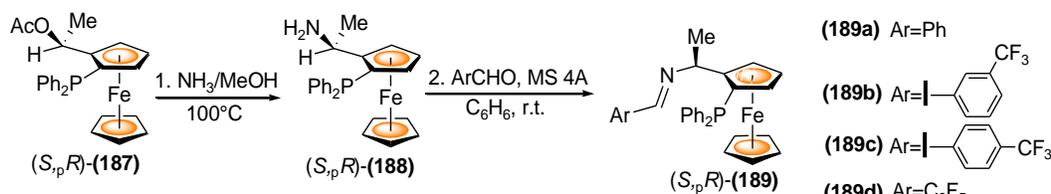
Scheme 37. Synthesis of optically active imino–phosphine ligands. [69]

In 2003 the novel synthesis of ferrocenylphosphine–aldimine and P–ketimine ligands [70] which were reported to be similar to the C$_2$ symmetric axially chiral binapthalene systems reported by M. T. Reetz *et al* were synthesised .[71] Using (R,$_p$$S$)–PPFNH$_2$–R **(188)** or **(191)** or (S,$_p$$S$)–PPFNH$_2$ **(188)** and reacting them with a variety of *m*–substituted acetophenones a number of potential P,N mixed donor ligands were synthesised **(Scheme 38)**. They reported for their

target compounds of **(192)** to have high yields and the **(193)** series all had yields that were low, none of which were over 65%. With respect to ($S,_pS$)–**(193c)** a yield of 57.1% was observed **(Scheme 39)**.
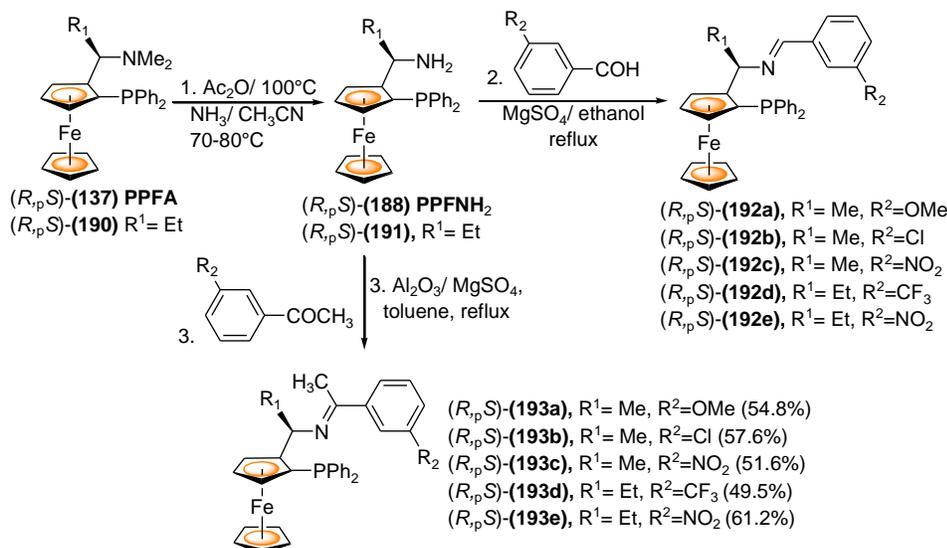
Scheme 38. Synthesis of ferrocenylphosphine–imine ligands ($R,_pS$)–**(192)** and ($R,_pS$)–**(193)**. [69]
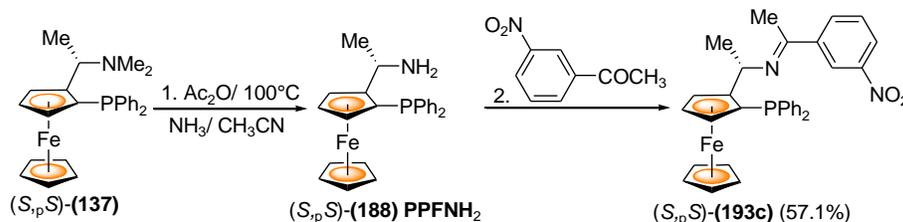
Scheme 39. Synthesis of ketimine ($S,_pS$)–**(193c)**. [69]

Boronato–functionalised ferrocenylphosphine ligands ($S,_pR$)–**(195a–c)** which were synthesised from ($S,_pR$)–1,1'–*bis*(diphenylphosphino)–2–[1((1–hydroxy–2–phenyl)amino)ethyl]–ferrocene ($S,_pR$)–**(194)** have been reported, [72] ($S,_pR$)–**(194)** was synthesised from complex ($S,_pR$)–**(187)** by refluxing in toluene with a large excess of 2–aminophenol for 18 hrs. The resulting boron–containing ferrocenyl ligands ($S,_pR$)–**(195a–c)** were obtained in good yields and are reported to be stable in air with no decomposition occurring **(Scheme 40)**. [72]
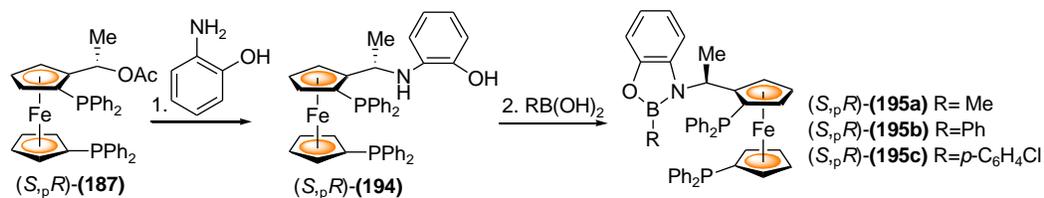
Scheme 40. Synthesis of boronato–functionalised ferrocenylphosphine ligands ($S,_pR$)–**(195a–c).** [72]

1.6.3 Synthetic Routes to 1,2–Unsymmetrical Ferrocenes *via* Nitrogen/Sulfur Exchange.

The sodium salt of (R)–1–[($_pS$)–(diphenylphosphino)ferrocenyl]ethyl mercaptan ($R,_pS$)–**(196)** was reacted with racemic epoxide to give a P,S,O system of diastereoisomers ($R,S,S,_pS$)–**(197)** and ($R,R,R,_pS$)–**(197)** (1:1) **(Scheme 41)**. The absolute configuration was determined using a single crystal of the oxidised phosphine from ($R,R,R,_pS$)–**(197).** [73]
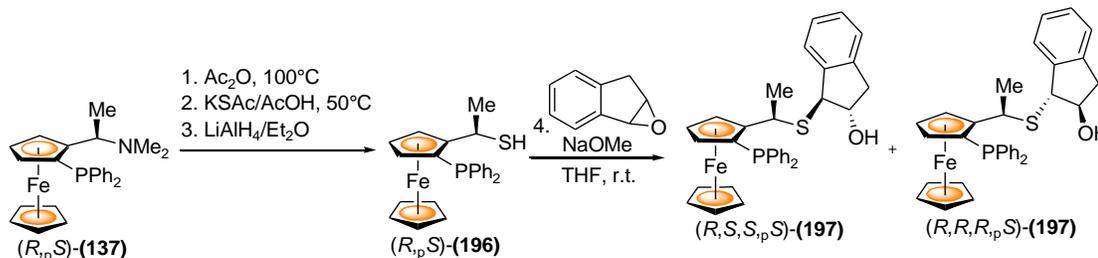
Scheme 41. Synthesis of P,S,O–ligands incorporating a planar chiral ferrocenyl motif. [73]

1.7   Synthetic Routes to 1,1' *Bis*–Substituted Planar Chiral Ferrocenes.

There are relatively few examples of 1,1' *bis*–substituted ligands which are C_2–symmeric and incorporate planar and/or planar–central chirality. [74–79] P. Knochel demonstrated an effective method of synthesis which initially involved a Friedel–Crafts acylation on a metallocene **(Scheme 42)**. This was followed by an asymmetric reduction of the ferrocenylketones using Corey–Bakshi–Shibata (CBS)–catalyst (oxazaborolidine) to give its corresponding (*S,S*)–diols in excellent enantiomeric excesses (all >98% *e.e.*). The diols were subsequently converted quantitatively to their acetates before being reacted with a primary amine to give a secondary amine. Treatment with an organolithium reagent was reported to result in the formation of a lithiated complex and subsequent reaction with chlorodiphenylphosphine gave C_2 symmetric complexes with exceptional enantiopurity. [74]–[79]
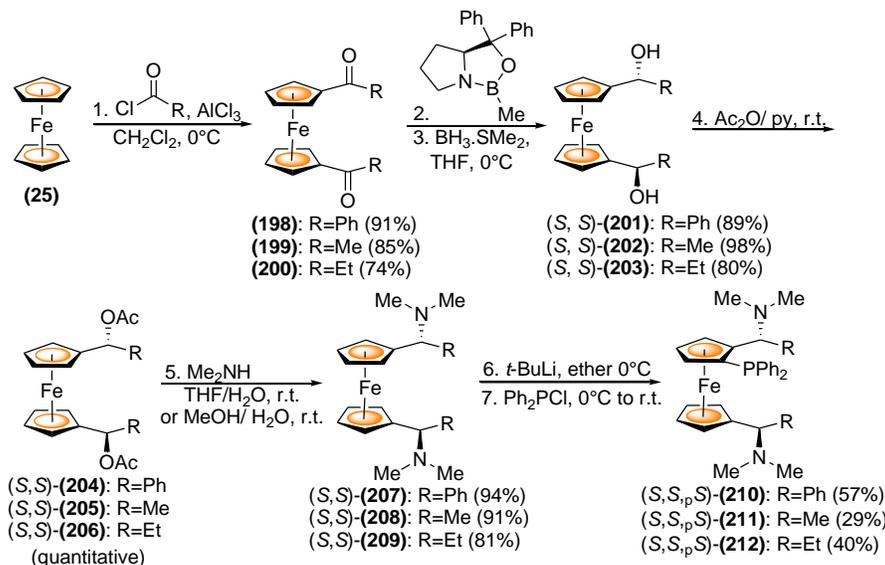
Scheme 42. Synthesis of C_2–symmetric diamino FERRIPHOS ligands. [75]

1.8   Alternative *Ortho*–Directing Groups.

1.8.1 Sulfoxide Derived *Ortho*–Directing Groups.

In addition to the 1–*(N,N*–dimethylamino)ethyl functionality, chiral sulfoxide groups following a similar mechanism have been used for *ortho* direction. There are two popular methods for the synthesis of chiral sulfoxides with the exception of resolution. The first is the K. K. Andersen method [80], [81] which involves converting sulfinates into sulfoxides using organometallics. The interesting feature of this method was reported to be inversion in the configuration at sulfur, an example of a sulfinate that can be used is (*R,R*$_S$)–menthyl *p*–tolyl sulfinate allowing crystallisation to be combined with acid catalysed epimerisation at sulfur. The second popular method used involves asymmetric oxidation of prochiral

sulphides, this method found to be very efficient *i.e.* between 95–96% *e.e.* when oxidants are used with a Sharpless reagent *i.e.* Ti(O*i*–Pr)$_4$/ (+)–DET/ H$_2$O in a 1:2:1 ratio. [82–89]

H. B. Kagan and co workers in 1991 reported the preparation of enantiomerically pure sulfoxides from chiral sulphite showing that they can be synthesised from cheap starting materials. For example chiral diol **(191)** can be made from ethyl lactate **(218)** and that cyclic sulphite both *trans* **(220)** and *cis* **(220)** can be prepared by reacting the diols in thionyl chloride **(Scheme 43)**. [90] In 1993 they reported the diastereoselective ortho lithiation of ferrocenyl sulfoxide, showing that the (*S*) chiral sulfoxide was a good directing group **(Scheme 43)**. Using (*R*)–ferrocenyl *p*–tolyl sulfoxide **(215)** {from ferrocenyl lithium with (+)–(*R*$_S$,*S*)–methyl *p*–tolylsulfinate **(214)**} using a modified method to avoid getting an inseparable mixture they demonstrated that a selective deprotonation can be achieved using lithium diisopropylamide (LDA) at –78°C in THF. They also reported that very high diastereomeric excess can be obtained when quenched with either trimethyl silyl chloride give (*R*,$_p$*R*)–**(216)** or tributlstannyl chloride to give (*R*,$_p$*S*)–**(217)**. [91]
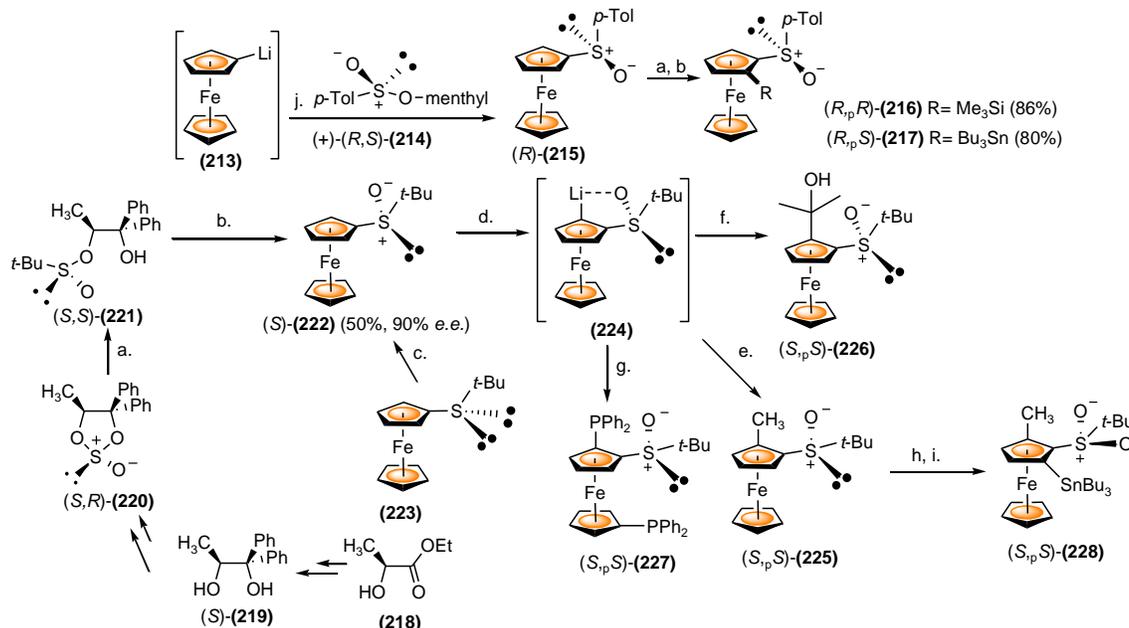
Scheme 43. Asymmetric synthesis of chiral ferrocene (*S*)–**(222)** and its diastereoselective *ortho*–functionalisation. a: *t*–BuMgCl, THF, –78°C (75%). b: 2 equiv. ferrocenylliyhium, THF (80%). c: Ti(O*i*–Pr)$_4$/ (*S*,*S*)–DET/H$_2$O (1:2:1), cumene hydroperoxide, CH$_2$Cl$_2$, –20°C (55%, 90% *e.e.*). d: 1:1 equiv. *n*–BuLi, THF, 0°C to room temp. e: CH$_3$I (80%): f: acetone (85%). g: 1). 1 equiv. *n*–BuLi, THF 0°C to room temp.: 2). Ph$_2$PCl (80%). h: magnesium monoperoxyphthalate (MMPP), EtOH, 0°C to room temp. (95%), i: 1). 1 equiv. *n*–BuLi, THF, –20°C: 2). *n*–Bu$_3$SnCl (51%). j: diastereoselective *ortho*–lithiation (>98% *d.e.*) of (*R*)–**(215)** a: LDA, THF, –78°C. b: RCl.

In 2004 J. C. Carretero and co–workers reported the lithiation of (η⁴–cyclobutadiene)(η⁵–cyclopentadienyl)cobalt using Schlossar super base (*t*–BuLi and *t*–BuOK). [92] The diastereoselective functionalisation at C–2 was achieved by treatment with (*R*$_S$)–**(230)** with 1.2 equivalents of *tert*–BuLi (THF, –78°C) followed by the addition of Ph$_2$PCl. The planar chiral metallocene (*R*$_S$,$_p$*R*)–**(231)** was reported be obtained in 84% yield with a diastereomeric excess of >99%. Subsequent reduction of the sulfoxide using HSiCl$_3$–Et$_3$N in refluxing toluene gave (*R*$_S$,$_p$*R*)–**(232)** 'Cosulphos ligand' in 86% yield and an enantiomeric excess of 99.5% **(Scheme 44)**.
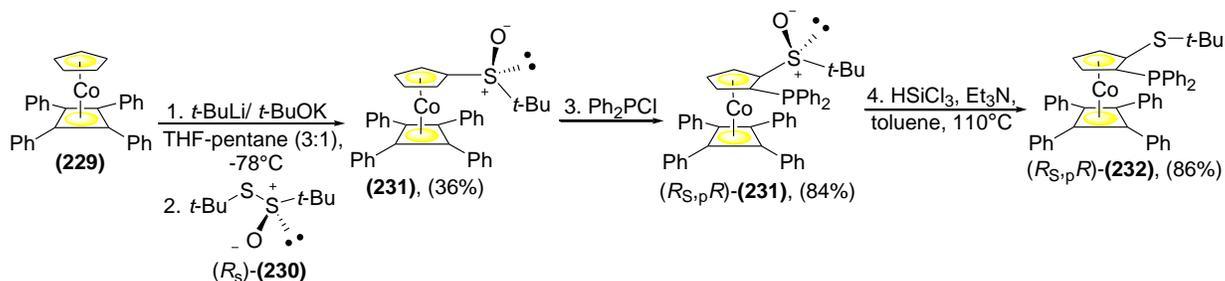
Scheme 44. Synthesis of an enantiopure organocobalt sulfoxide (R_S,$_pR$)–**(232)**. [92]

In 2005, [93] the synthesis of (S)–**(234)** was reported, using the procedure developed by J. C. Carretero (modified version of the Anderson method) which used (R_S)–**(230)** and was found to give a better yield of 68% yield and >99% enantiomeric excess. In the same paper they also reported the synthesis of (S)–cyclohexylsulfinylferrocene which has a group on sulfur that is less hindered compared to the *tert*–butyl group. The chiral source was reported to be synthesised using Khiar–Alcudia dynamic kinetic resolution based on D–glucose. [94], [95] (S)–**(235)** was evidence that this type of directing group was ineffective because a competing reaction takes place as a result of the acidic proton present alpha to the sulfinyl group **(Scheme 45)**.
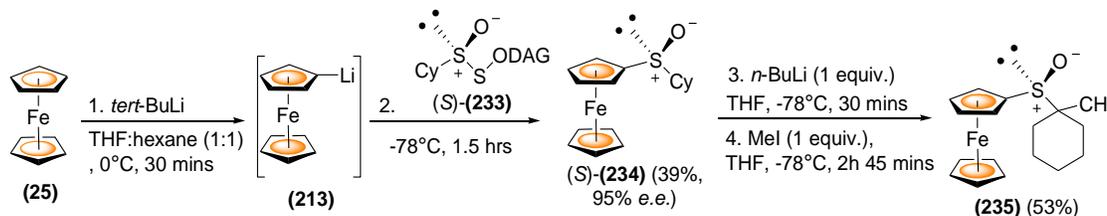
Scheme 45. Synthesis of cyclohexylsulfinylferrocene (S)–**(234)**. [93]

Sulfoxide lithium exchange was reported in an excellent review by B. Ferbera and H. B. Kagan to allow transformations and a library of planar chiral derivatives to be made *via* electrophilic quenching of the intermediate lithioferrocene **(Scheme 46)**. The yields were reported to be improved by using *t*–BuLi and by controlling the temperature or by use of PhLi with inverse addition. Various polysubstituted metallocenes which are planar chiral were synthesised. Moreover either Suzuki or Negishi cross coupling allowed 1,2–disubstituted planar chiral complexes to be synthesised **(Scheme 47)**. 1,3–disubstituted planar chiral complexes were synthesised *via* a double ortho direction **(Scheme 48)**. [96]
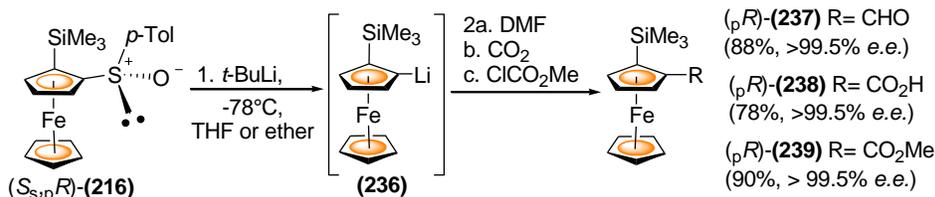
Scheme 46. Synthesis of enantiopure 1,2–disubstituted ferrocene sulfoxides. [96]
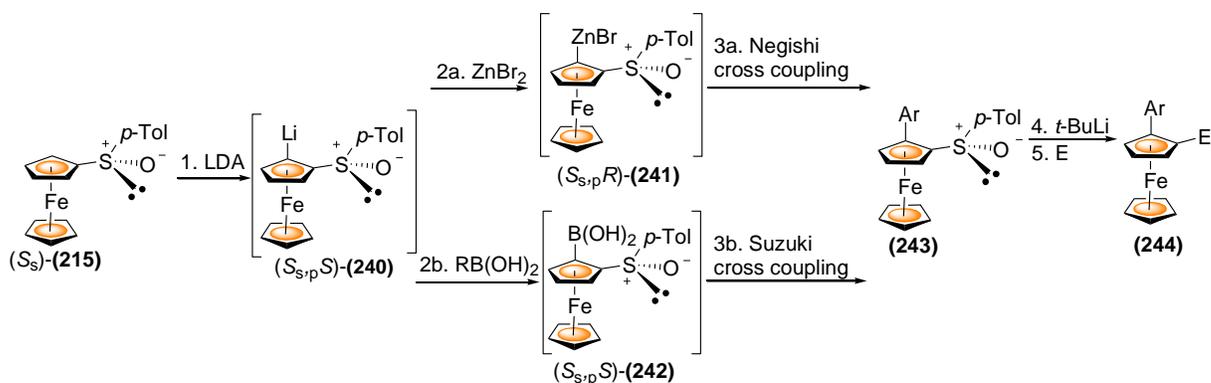
Scheme 47. Suzuki or Negishi couplings on a ferrocene sulfoxide. [96]
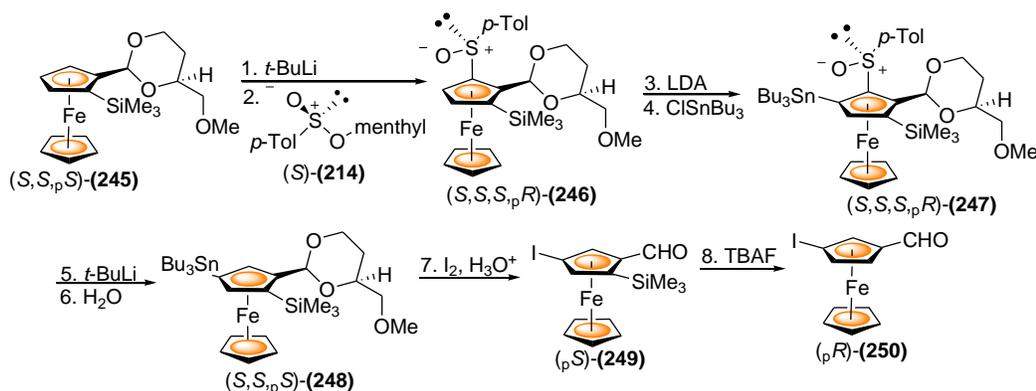
Scheme 48. 1,3– or 1,2,3–susbtituted chiral ferrocenes. [96]

1.8.2 Aldehyde/Ketone Derived *Ortho*–directing Groups.

Acetal derived *ortho* directing groups have been reported to be used to synthesise planar chiral metallocenes. The acetal complex **(251)** is synthesised from ferrocenecarboxaldehyde and (*S*)–1,2,4–butanetriol in good yield (80%). When **(251)** is treated with *tert*–butyllithium at –78°C and then warmed to room temperature, the reaction takes place under kinetic control to give a diastereoselective lithiation (98% *d.e.*). It is reported that by quenching the reaction with an appropriate electrophile such as chlorodiphenylphosphine planar chiral ferrocenyldehydes can be synthesised in 98% enantiomeric excess **(Scheme 49)**. The auxiliary was also reported to be recoverable. [97–99] **Scheme 50,** illustrates the enantiopure synthesis of **(258)** which is an example of an oxaferrocenophane. [98]
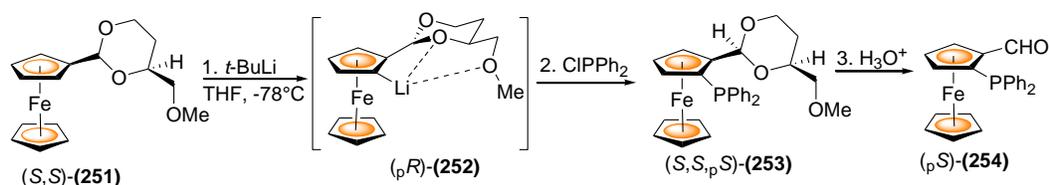
Scheme 49. Synthesis of planar chiral ferrocenyldehydemetallocenes. [97–99]
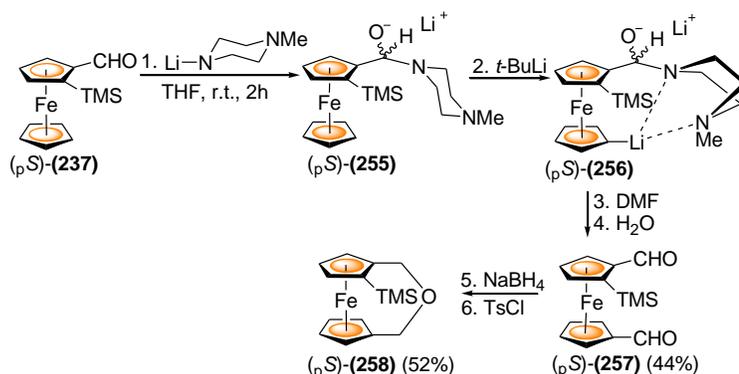
Scheme 50. Novel method for the synthesis of an oxaferrocenophane (_pS)–**(258)**. [100]

1.8.3 Oxazoline Containing and Derived *Ortho*–directing Groups.

G. Helmchen, [101], [102] A. Pfaltz [103], [104] and J. M. J. Williams [105], [106] independently synthesised P,N chiral oxazoline ligands **(258)** and showed the enormous potential of ligands of this nature in asymmetric catalysis **(Figure 20)**. The properties that make them so effective with respect to asymmetric catalysis are the fact that they possess hard and soft donor atoms. [107], [108] Consequently the unique properties of each atom were proven to induce different types of reactivity in metal complexes. [109]

(258) 'PHOX'
R= *i*-Pr, *t*-Bu, Ph, Bn

(259) 'Phosphinooxazoline'
R= *i*-Pr, *t*-Bu, Ph, Bn
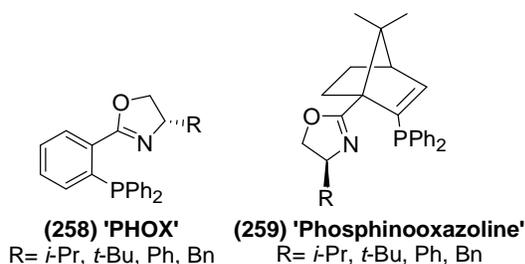
Figure 20. First generation oxazoline ligands. [101]–[106]

Three research groups; C. J. Richards, [110] T. Sammakia [111] and S. Uemura [112] exploited the *ortho* directing nature (lithiation) of the oxazoline moiety on ferrocene. They reported a significant improvement could be made on diastereomeric excess by fine tuning experimental reaction conditions. For example, 2.5:1 when *n*–BuLi was added at room temp., 8:1 when *s*–BuLi was added at –78°C in THF, 39:1 when *s*–BuLi was used at –78°C in Et$_2$O and finally addition of TMEDA with *s*–BuLi in either Et$_2$O or hexane was found to give exceptional selectivity of >500:1 with a 94% yield (Et$_2$O) and >500:1 with a yield of >75% (hexane) **(Scheme 51)**.

To prove that the *ortho* directing lithiation was mediated by nitrogen as opposed to oxygen, a macrocyclic ferrocenyloxazoline was synthesised **(Scheme 52)**. The linker group prevented rotation across the ferrocene–oxazoline bond. Moreover, when the oxazoline was orientated towards the iron (Fe) this was postulated to allow the nitrogen–coordinating alkyl lithium reagent to approach unrestricted and unconstrained adjacent to it or in a *syn* orientation (sterically hindered). Thus, only one diastereoisomer was detected. The information that was drawn from this was poor selectivity observed in systems that were not macrocyclic in nature and as a result of a competing pathway utilising less sterically encumbered oxygen. [114]
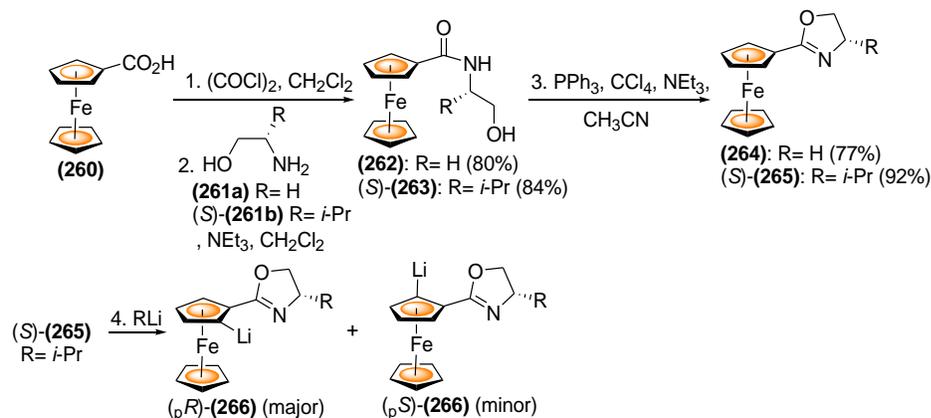
Scheme 51. Synthesis of *ortho* directed compounds from ferrocenyloxzoline. [(110)–(114)]
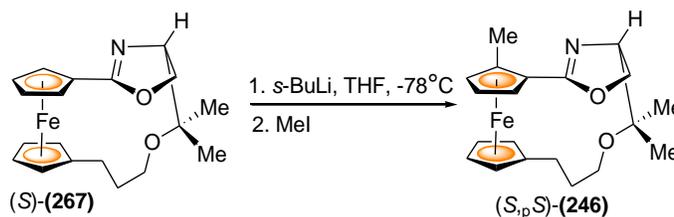
Scheme 52. Synthesis of macrocyclic ferrocenyloxzoline **(246)**. [(114)]

Several ligands were synthesised as a consequence of quenching the reaction with chlorodiphenylphosphine. The synthesis of *e.g.* (S,$_p$S) phosphinoferrocenyloxazoline (phosferrox) **(270a)** in 64% yield **(Scheme 53)** proved to be an effective ligand for asymmetric catalysis. The synthesis of (S,$_p$R)–diastereoisomer of **(270a)** was demonstrated *via* the addition of a removable trimethylsilyl blocking group **(Scheme 54)**. [(115), (116)]
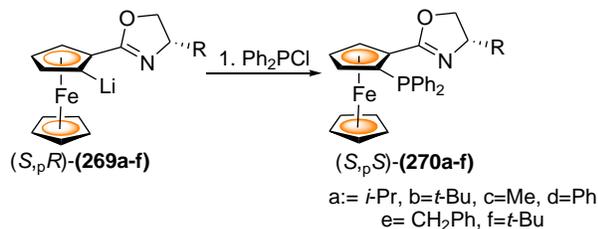
Scheme 53. Synthesis of (S,$_p$S) phosphinoferrocenyloxazoline complexes **(270)**. [(115), (116)]
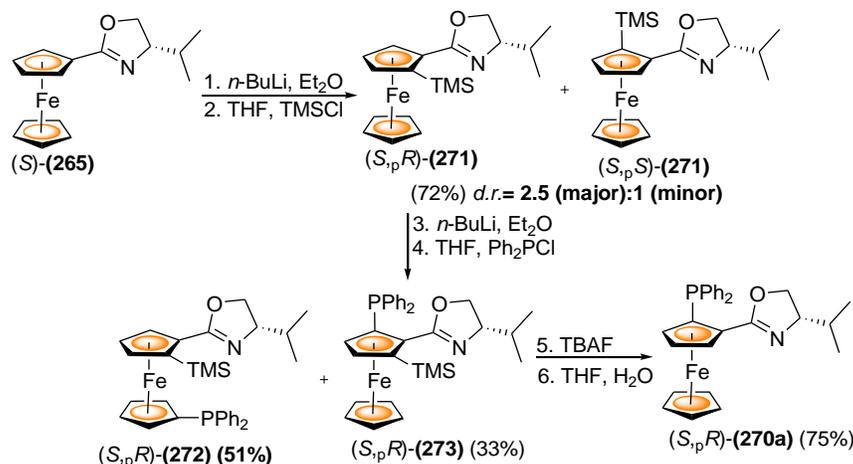
Scheme 54. Synthesis of (S,$_p$R) phosphinoferrocenyloxazoline complexes. [(115), (116)]

Additional substituents on the oxazoline moiety were found to improve selectivity as reported by S. Uemura *et al.* Based on this information J. Park, K. H. Ahn and I. Ikeda reported the lithiation and phosphination of (*S,S*)–**(274)** to give (*S,S,*p*S*)–**(275)** in a 40% yield and (*S,S,*p*R*)–**(275)** in a 28% yield **(Scheme 55)**. [117], [118]
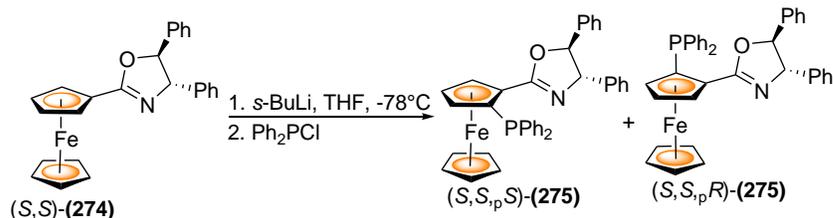
Scheme 55. Synthesis of planar chiral metallocenes **(275)**. [117], [118]

Stereochemical control of *ortho*–metallation using palladium salts was demonstrated using the metallocene (η^4–tetraphenylcyclobutadiene)(η^5–cyclopentadienyl)cobalt(I) to create Lewis acidic palladium based catalysts *i.e.* (+)–(p*R*)–**(279)**. [119] The orientation in the diastereoselective palladation was reported to be determined using NOE spectroscopy. The p*R* absolute configuration was later confirmed by L. Overman and co–workers [120] using X–ray crystallography which were coincidently studying the same ligand **(Scheme 56)**. C. J. Richards reported *ortho* metallation for a pentaphenylferrocene derivative [121] and *tert*–butyl–leucine–derived cobalt oxazoline complexes. [122]
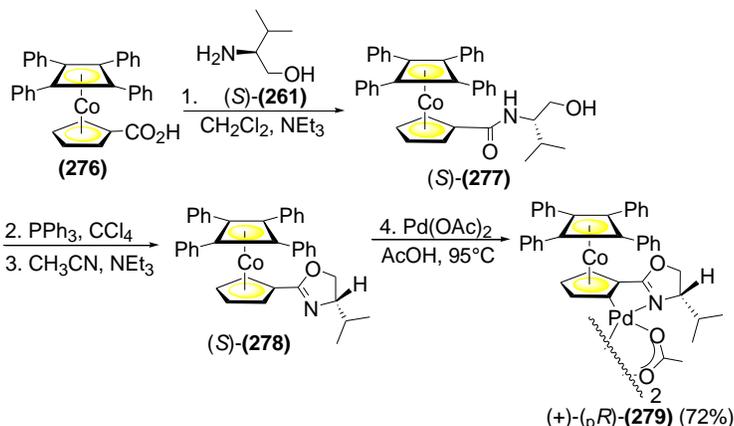
Scheme 56. Synthesis and highly diastereoselective palladation of η^5–(*S*)–2–(4–methylethyl)oxazolinylcyclopentadienyl) (η^4–tetraphenylcyclobutadiene)cobalt **(279)**. [119]

1.8.4 Other Auxiliary Derived *Ortho*—Directing Groups.

A further example of an *ortho* directing group which is an auxiliary that induces a diastereoselective *ortho* lithiation is shown in **(Scheme 57)**. Reaction between ammonium iodide **(280)** and (*S*)–2–methoxymethylpyrrolidine (SMP) **(281)** gave (*S*)–(2–methoxymethylpyrrolidin–1–yl)ferrocene **(282)** (86% yield). Using *s*–BuLi in Et$_2$O at –78°C followed by the addition of Ph$_2$PCl was reported to result in the production of **(283)** with a very good diastereomeric excess of 98%. Subsequent cleavage of **(283)** gave **(284)**. *Ortho* functionalisation was also reported to be achieved by using a neutral chiral formyl anion and cyanide equivalent (*S*)–1–amino–2–methoxymethyl–pyrrolidine or SAMP hydrozone which is synthesised from benzoylferrocene (73% yield). [123]
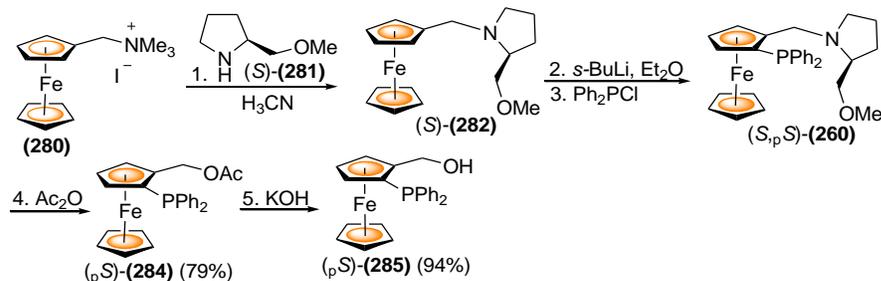
Scheme 57. Diastereoselective *ortho* lithiation using auxiliary. [123]

The *ortho* directing effect involving lithiation with *n*–BuLi in Et₂O at –70°C followed by quenching the reaction with electrophiles was reported to give several important adducts **(287a–f)** in good yields and reasonably good diastereoselectivity. [124] An oxidative cleavage of the hydrozone with ozone for instance, or a reductive cleavage using SnCl₂ or TiCl₃ gave benzoylferrocenes **(288a–f)**. The vast majority of the ketones that were isolated had an enantiomeric purity of 90–96% although **(288f)** was reported to have an *e.e.* of only 71% **(Scheme 58)**. [124]

a: R=Me, b: R=TMS, c: R=Ph,
d: R=C(OH)Ph₂, e: R=CHO, f: R=I
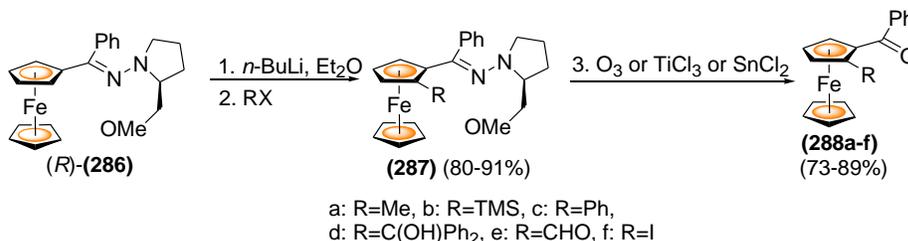
Scheme 58. Diastereoselective *ortho* lithiation followed by quenching with electrophile. [124]

R. Kitzler *et al* reported the *ortho*–lithiation of *N*–ferrocenylmethyl–*O*–methyl ephedrine (98% *d.e.*) (*R,S*)–**(289)**. *O*–Methyl ephedrine was reported to be synthesised from (*R,S*)–*O*–methyl ephedrine which was prepared from (ferrocenylmethyl)triethylammonium iodide in 88% yield. *Ortho*–Lithiation of (*R,S*)–**(289)** with *tert*–BuLi followed by addition of an electrophile (E=Ph₂PCl, I₂, Ph₂C=O) yielded 1, 2–disubstituted ferrocenylmethyl derivatives **(290a–c)** {**(290a)**, 90%; **(290b)**, 84%; **(290c)**, 64%} all with >98% *d.e.* **(Scheme 59)**. To demonstrate that the chiral auxiliary can be replaced the major diastereoisomer of **(290a)** was treated with acetic anhydride to give (ₚ*R*)–**(291)** in 90% yield and 98% diastereomeric excess **(Scheme 60)**. [125]
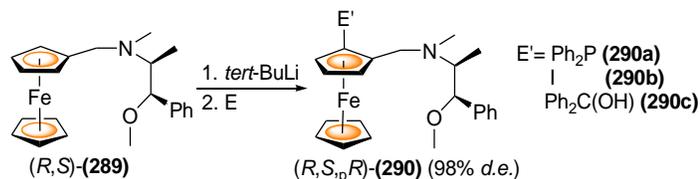
Scheme 59. *Ortho*–lithiation of *N*–ferrocenylmethyl–*O*–methyl ephedrine. [125]
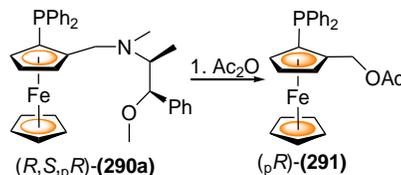
Scheme 60. Relatively simple reaction conditions for the removal of auxiliary. [125]

It was observed experimentally that the *ortho*–lithiation of (*R*,*S*)–**(289)** was affected by temperature as well as solvent and lithiation reagent. By using *tert*–BuLi in Et$_2$O as opposed to pentane and I$_2$ as the electrophile, the diastereoselectivity was found to decrease (86%). However the reaction of (*R*,*S*)–**(289)** with *sec*–BuLi and I$_2$ in pentane gave (*R*,*S*,$_p$*S*)–**(290b)** with a 79% *d.e.* But when diethyl ether was used the diastereoselectivity improved. When quenched with Ph$_2$PCl or I$_2$, (*R*,*S*,$_p$*S*)–**(290a)** and (*R*,*S*,$_p$*S*)–**(290b)** were obtained with 80% *d.e.* However the major diastereomer had a ($_p$*S*) configuration at the ferrocene unit. In order to assign the complex (*R*,*S*,$_p$*S*)–**(290b)** was converted into 2–iodo–1–dimethylaminomethylferrocene **(292)**, of known absolute configuration and through correlation studies absolute configuration assigned **(Scheme 61)**. [125]
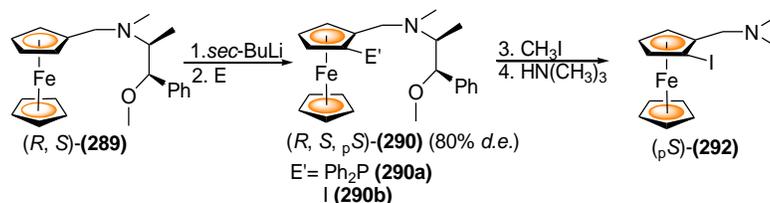
Scheme 61. Demonstration of the effect reaction conditions have on (*d.e.*). [125]

Complex (*S*$_a$,$_p$*S*)–**(296)** is an example of a chiral aminophosphine ligand which was made *via* a diastereoselective *ortho*–lithiation of the aminoferrocene (*S*$_a$)–**(295)**. Complex **(294)** was found to be easily synthesised using methyl iodide and heating the mixture in aqueous ammonia/benzene for 48 hours in an autoclave (80%). The primary amine was cyclised using (*S*)–2,2'–*bis*(bromomethyl)–1,1'binaphthyl to give (*S*$_a$)–**(295)** in 79%. When (*S*$_a$)–**(295)** was treated with *s*–BuLi/Et$_2$O followed by chlorodiphenylphosphine it gave (*S*$_a$,$_p$*S*)–**(296)** in 65% yield. Although attempts were made to improve the diastereoselectivity *i.e.* by changing the reaction conditions the diastereoselectivity was found to be still 9:1. The relative configuration of (*S*$_a$,$_p$*S*)–**(296)** was determined using X–ray crystallography **(Scheme 62)**. [127]–[129]
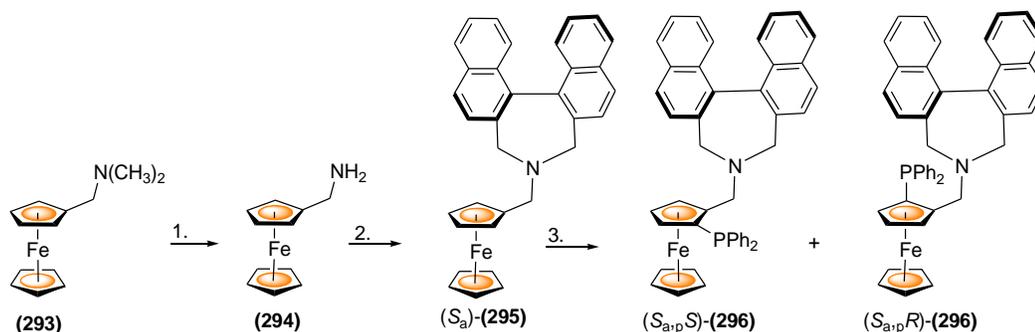
Scheme 62. Synthesis of chiral aminophosphine ligands (Reagents; 1. MeI, conc. ammonia/ benzene 100°C, 48 hours, (80% yield); 2. (*S*)–2,2'–*bis*(bromomethyl)–1,1'–binapthyl, triethylamine, benzene, reflux, 18 hours (79% yield); 3. (a) *s*–BuLi, ether, room temp., 4 hours, (b) chlorodiphenylphosphine, –78°C →room temp., (65% yield). [127]–[129]

1.9   Synthesis of Planar Chiral Heterocycle Metallocenes.

The synthesis of chiral nucleophilic catalysts is very challenging because of the low yields reported and difficulty in resolution *e.g.* semi preparative HPLC. [130]–[132] This problem of catalyst resolution was addressed by introducing a readily available source of chirality into heterocycle where the asymmetric environment of the nucleophilic nitrogen (N) is controlled by attachment to a bulky cobalt metallocene. **Figure 21** shows an X–ray crystal structure of an imidazole

metallocene in the solid state this was found to be the major conformer in solution state confirming the nitrogen atom is in an environment of virtual planar chirality. [133]
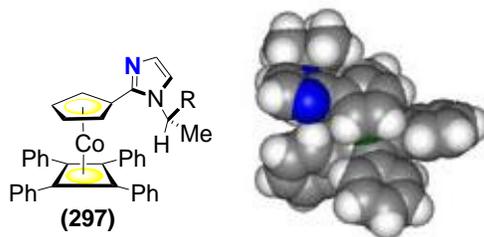
Figure 21. Control of the configuration of the heterocycle for use in nucleophilic catalysis. [133]

This approach was adopted with **(298)** itself to give cobalt metallocene appended derivative **(302)** which was synthesised in three steps from (*S,S*)–hexane–2,5–diol **(303)** **(Scheme 63)**. Stereochemical information in C_2–symmetric pyrrolidine substituent is relayed to the pyridine nitrogen of bulky cobalt–based metallocene. Complex **(307)** is a C_2–symmetric variant of **(302)** and **(300)** **(Scheme 64)**. [134]
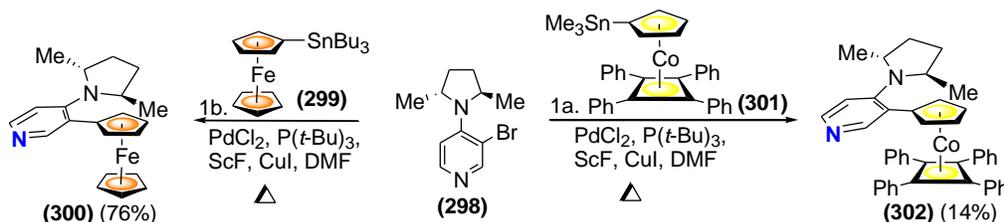
Scheme 63. Synthesis of C_1–symmetric nucleophilic catalyst **(300)** and **(302)**. [134]
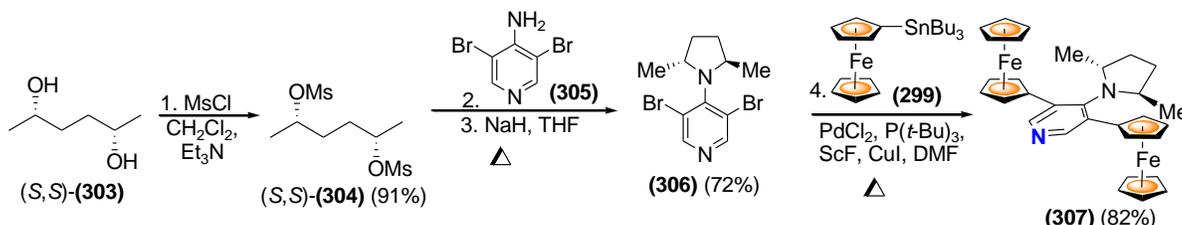
Scheme 64. Synthesis of C_2–symmetric nucleophilic catalyst **(307)**. [134]

1.10   Planar Chiral Ansa Metallocenes Synthesis.

Ansa metallocene derivatives with substituted covalently–bridged ligands are a class of stereorigid chiral organometallic compounds. Group 4 metallocenes for instance are characteristically d^0 and have a pseudo tetrahedral geometry with the transition metal bearing two η^5 cyclopentadienyl ligands and two σ–ligands. Both the cyclopentadienyl ligands remain attached to the metal during polymerisation and often define the stereoselectivity and activity.

In the early 1980s H. H. Brintzinger and co workers showed examples of interconnection of both cyclopentadienyl ring ligands by an ethylene bridge which results in stabilisation of bent metallocenes derivatives of group IV transition metals. In 1985, ethylene–bridged titanocene and zirconocene derivatives with permethylated ring ligands were synthesised *i.e.* $C_2H_4(C_5(CH_3)_4)_2TiCl_2$ and $C_2H_4(C_5(CH_3)_4)_2ZrCl$ with their crystals structures determined. [136] Also during this period (1982) the synthesis and molecular structures of chiral ansa–titanocene derivatives with bridged tertahydroindenyl ligands, in particular racemic ethylene–*bis*(4,5,6,7–tetrahydro–1–indenyl)titanium dichloride, were

reported. [137] The early application as a result of the performance of Ziegler–Natta heterogeneous catalyst systems (TiCl$_4$/AlEt$_3$) (1954) and VCl$_4$/AlR$_3$ (1962) influenced the design of subsequent complexes. To put this work in context, homogenous metallocene catalysts were applied to polymerisation of propylene.

J. A. Ewen *et al.* made the first stereospecific bridged metallocene catalyst [*rac*–ethyliden*bis*(indenyl)titanium dichloride/MAO (methylalumoxane, co–catalyst)] (diastereoisomers not separated) they generated isotactic (63%) and atactic in (37%) products **(Scheme 65)**. [138] However, it was H. H. Brintzinger and K. Kaminsky (discovered MAO co–catalyst) that effectively reported a pure *rac* catalyst to give highly isotactic polypropylene demonstrating high molecular weight PE with unprecedented catalytic activity (106g PE/gzr.hr.bar) which was higher than the commercially available Zeigler–Natta catalysts **(Scheme 66)**. [139] Subsequent research in this area ascertained that in terms of the stereochemical rationale the catalyst controlled the initial insertion step as opposed to the last insertion of the asymmetric centre on the polymer chain. [140]–[144] Two important reviews have discussed the synthesis and application of ansa metallocenes. [145], [146]
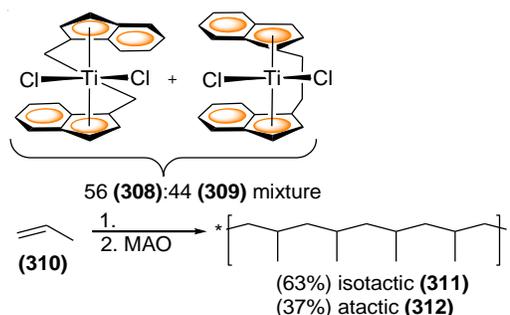
Scheme 65. Early example of application of a mixture of **(308)** and **(309)**. [138]
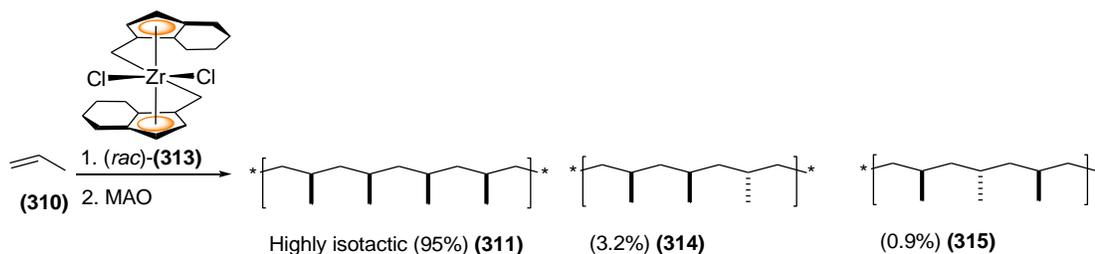
Scheme 66. Application of *rac*–**(313)** and polymerisation outcome. [139]

The dilithiation of (*R*)–1–methyl–9–[2–(2–indenyl)–1–napthyl]fluorene **(317)**, which generated an axially chiral fluorenyl ligand was reported, [147] (*S$_a$*)–**(318)** when reacted with ZrCl$_4$ in an enantiospecific reaction gave a planar chiral ansa zirconocene (*$_p$S*)–**(319) (Scheme 67)**. The enantiomeric purity of (*$_p$S*)–**(319)** was determined by conversion using a benzene solution of (*$_p$S*)–**(319)** and treatment with glacial acetic acid to give quantitative recovery of (*S$_a$*)–**(317)**. [147]
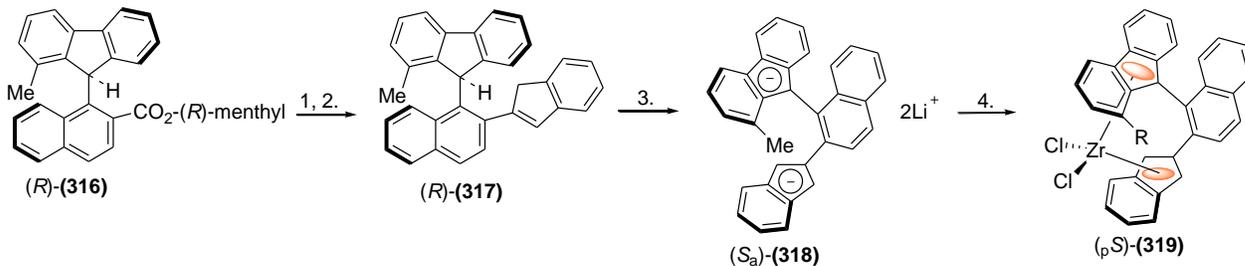
Scheme 67. Synthesis of ansa metallocene ($_pS$)–**(319)**. Reagents and conditions: 1. 1,2–$C_6H_4(CH_2MgCl)_2$ (1.5 equiv.), THF, –78 to 25°C, 16 h; 2. TsOH (0.05 equiv.), benzene, reflux, 15 min; 3. *n*–BuLi (2.4 equiv.), THF, 0°C, 60 min; 4. $ZrCl_4$ (1.1 equiv.), benzene, 25°C, 90 min. [147]

M. D. LoCoco and R. F. Jordan recently reported a general and efficient method for the enantioselective synthesis of ansa–metallocenes. Previously they reported a diastereoselective 'chelate–contolled' synthesis of racemic ansa metallocenes using Li[Cp'XCp'] salts with chelated *bis*–amide compounds Zr{RN(CH_2)_3NR}Cl_2(THF)_2; R=Ph, SiMe_3 **(320)** illustrated in **Scheme 68**. [148]
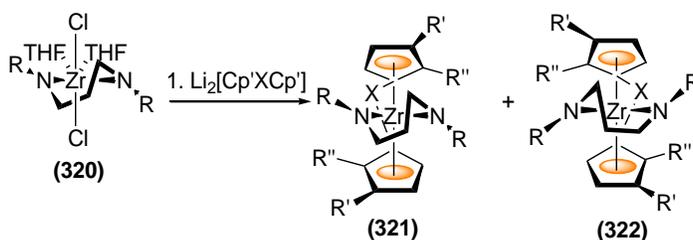
Scheme 68. Diastereoselective 'chelate–contolled' synthesis of racemic ansa metallocenes using Li[Cp'XCp']. [148]

The reaction of $ZrCl_4(THF)_2$ and (*R,R*)–**(326)** (1 equiv.) gave **(328)**. When (*R,R*)–**(326)** was reacted with Li_2[SBI](Et_2O) **(327a)** {SBI=(1–indenyl)_2SiMe_2} or Li_2[EBI](Et_2O) **(327b)** {EBI=1,2–(1–indenyl)_2ethane} it gave metallocene (*S,S*)– (SBI)Zr{(2*R*,4*R*)–HNCHMeCH_2CHMeNPh} (*S,S,R,R*)–**(328a)** or (*S,S*)–(EBI)Zr{(2*R*,4*R*)–PhNCHMeCH_2CHMeNPh} (*S,S,R,R*)–**(328b)** in >95% isolated yield. ^{1}H NMR was used to confirm a single set of resonances for isolated **(328a,b)** and HPLC confirmed >99.5% *e.e.* Using compound **(328b)** was converted to the corresponding enantiomerically pure dichloride (*S,S*)–**(328b)** in 91% yield and >99% *e.e.* in a reaction involving HCl in Et_2O **(Scheme 69)**. [148]
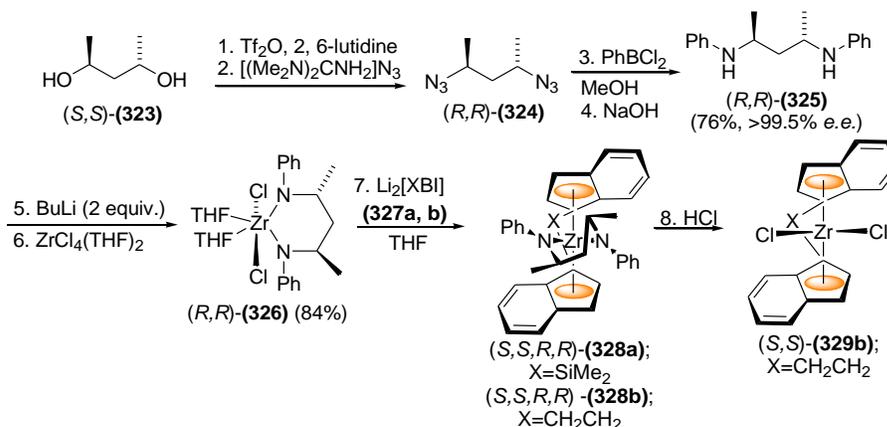
Scheme 69. Application of the stereo defined complex (*R,R*)–**(326)** in the synthesis of (*S,S,R,R*)–**(328a)** and (*S,S,R,R*)–**(328b)**. Addition of HCl to the latter results in (*S,S*)–**(329b)**. [148]

1.11 Planar Chirality in Paracyclohanyl Systems.

The previous sections have described how to generate planar chirality in metallocenes and ansa metallocenes. However planar chirality can also be generated in 'metallocene like' systems first reported by H. J. Reich and D.J. Cram that are [2.2]paracyclophanes. [149] Unlike their metallocene counterparts they only require one substituent in order to make them planar chiral **(Figure 22)**. Remarkable similarities exist between both ferrocene and [2.2]paracyclophanes concerning their stability and the fact that they have two eclipsing rings. However the single drawback of [2.2]paracyclophanes has always been thought to be the unreactive nature of the system. **Scheme 70** illustrates a route to synthesis of [2.2]paracyclophane. [150]
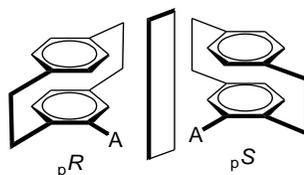
Figure 22. Planar chirality in paracyclophanyl systems. [149]
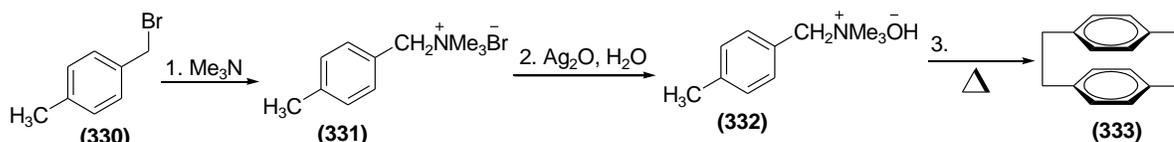
Scheme 70. Synthesis of [2.2]paracyclophane. [150]

In recent years there has been a resurgence of the chemistry related to planar chiral [2.2]paracyclophane. [151]–[157] Enantiomerically pure derivatives have been used in asymmetric catalysis. [158], [159] With the most well known being the C_2 symmetric 'PHANEPHOS' (R)–**(149) (Figure 19)** by K. Rossen and P. J. Pye**. [54],**

In 2009 an effective route to synthesis of novel enantiomerically enriched [2.2]paracyclophane–4–thiol using chiral sulfoxide (R_S)–**(335)** and planar chiral benzothiazole was reported **(Scheme 71, 72)**. [160] This example is significant as the planar and centrally chiral paracyclophane synthesis is an area that is relatively uncultivated. The reason for this has been ligand synthesis in the context of asymmetric catalysis is driven by results gained from their application. Hence other types of planar chiral systems have been investigated vigorously as opposed to this one until now.
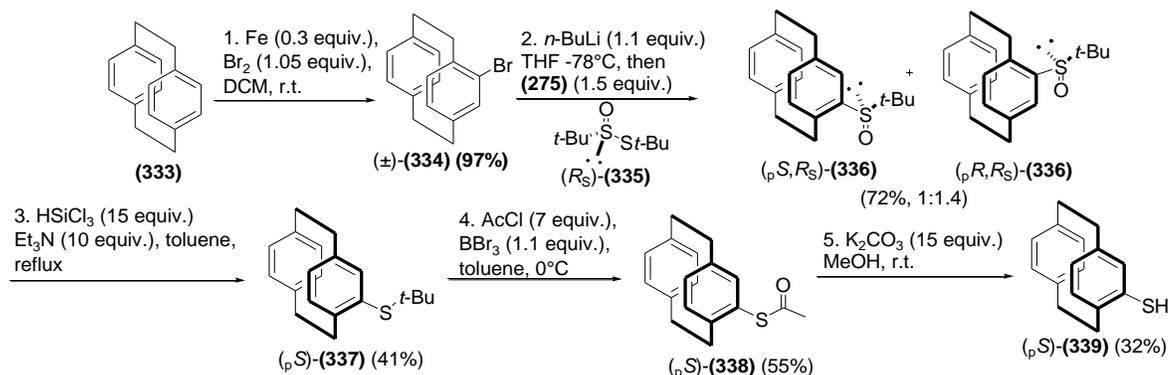
Scheme 71. Conversion of [2.2]paracyclophane to enantiomerically enriched [2.2]paracyclophane–4–thiol. [160]
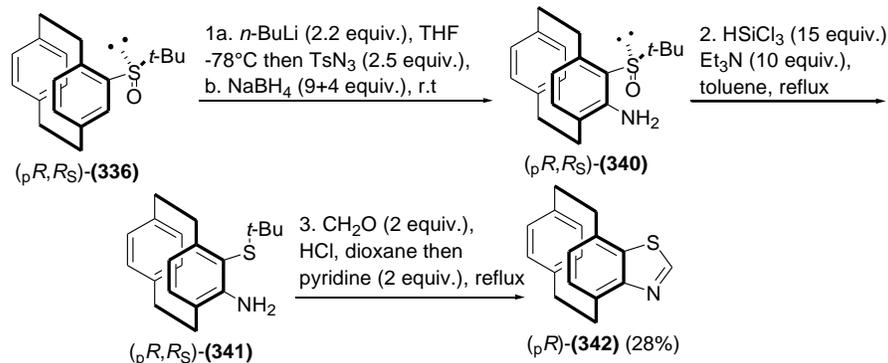
Scheme 72. Synthesis of [2.2] (4,7)benzo[*d*]thiazoloparacyclophane (pR)–**(342)**. [160]

1.12 Conclusions.

The purpose of this review was to show the increasing potential and methods that have been devised for enantioselective synthesis of planar chiral metallocenes. It is evident from this review that enzyme mediated resolution is a good method for the synthesis of planar chiral metallocenes and agrees with the general trend for the production of homochiral molecules. This is because they accept a wider range of substrates and display high levels of chemo, regio and enantioselectivity. Due to the performance of the new generation of chiral enzymes they now cost less and are readily available. It can be reasoned that this method is suitable for large scale reactions because lipases are currently used as key step for the majority of large scale industrial reactions to make drugs and chiral building blocks. The enzyme mediated approach is totally different from the Ugi *et al.* method that uses *N,N*–dimethyl–1–ferrocenylethylamine followed by diastereoselective *ortho* lithiation with butyl lithium followed by quenching using an electrophile. Although also effective for the generation of planar chiral metallocenes more steps and resources are needed. Similarly, this also applies for alternative *ortho* directing units such as a chiral acetals, oxazolines and sulfoxides.

Chapter Two

STEREOCHEMICAL BEHAVIOUR OF DICOBALT HEXACARBONYL PROPARGYL CATIONS AND THEIR REACTION WITH NUCLEOPHILES.

2.0   Introduction.

The synthesis of enantiopure metallocenes has often followed a three step sequence of synthesis. 1). Metallocene synthesis. 2). Introduction of a chiral auxiliary or a fixed stereogenic centre. 3). Diastereoselective attachment of a second substituent leading to a new element of planar chirality. The ease with which auxiliaries can be introduced and then removed makes it very effective. However, an alternative approach which has enomorous potential is the synthesis of planar chiral metallocenes *via* a diastereoselective complexation. The viability of this technique was demonstrated in our own research group by C. J. Taylor who initially started the project whereby she reacted racemic diynes with (η^5–C$_5$H$_5$)Co(CO)$_2$ **(106)** and synthesised novel planar chiral cobalt cyclopentadienone metallocenes **(347)**, **(348)**, **(349)** and **(350)** achieving relatively good diastereomeric ratios (*d.r.*) **(Scheme 73)**.[161] Although no planar chiral (η^4–cyclobutadiene)cobalt metallocenes were detected even though reactions were repeated using conditions like irradiation with light previously used in the literature **(Scheme 75–78)**. [162]–[165] She was only able to demonstrate through microwave assistance that diastereoselectivities of up to 5:1 can be obtained for planar chiral metallocyclopentadienone complexes. The experimental results are illustrated below **(Table 8)**. The scalemic metallocenes of **(350)** were obtained in 39% yield with no loss in the integrity of the absolute stereochemistry *i.e.* 72% enantiomeric excess carried through diastereoselective complexation to metallocene synthesis from enantioenriched chiral propargylic alcohol **(Scheme 74)**. Analysis of the tabulated results suggested that diastereoselectivity is a consequence of kinetic control.

(*rac*)-**(343)** R$_1$= Me, X= CH$_2$
(*rac*)-**(344)** R$_1$= *i*-Pr, X= CH$_2$

(*rac*)-**(345)** Ph, R$_1$= Me, X= *o*-C$_6$H$_4$CO
(*rac*)-**(346)** Ph, R$_1$= *i*-Pr, X= *o*-C$_6$H$_4$CO

($S_{,p}S$)*-**(347)**
($S_{,p}S$)*-**(348)**

($S_{,p}R$)*-**(347)**
($S_{,p}R$)*-**(348)**

($S_{,p}S$)*-**(351)**
($S_{,p}S$)*-**(352)**

($S_{,p}R$)*-**(351)**
($S_{,p}R$)*-**(352)**

($S_{,p}R$)*-**(349)**
($S_{,p}R$)*-**(350)**

($S_{,p}S$)*-**(349)**
($S_{,p}S$)*-**(350)**

($S_{,p}R$)*-**(353)**
($S_{,p}R$)*-**(354)**

($S_{,p}S$)*-**(353)**
($S_{,p}S$)*-**(354)**
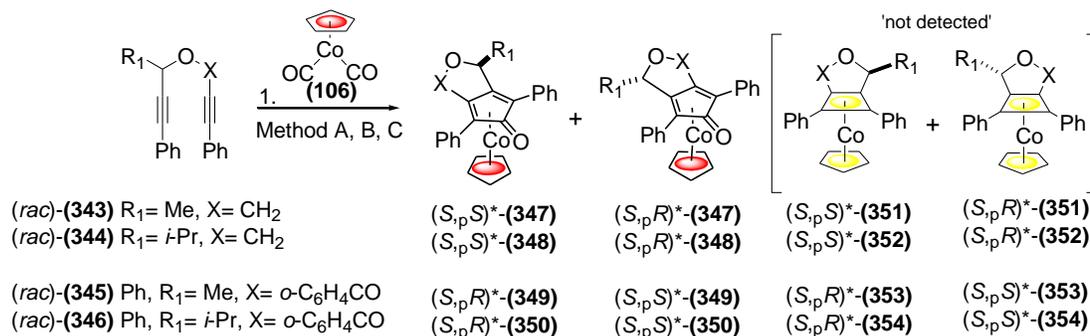
Scheme 73. Synthesis of planar chiral cobalt metallocenes *via* diastereoselective complexation. [161]

(*S*)-**(346)**   (*R*,$_p$*S*)-**(350)**   (*S*,$_p$*S*)-**(350)**
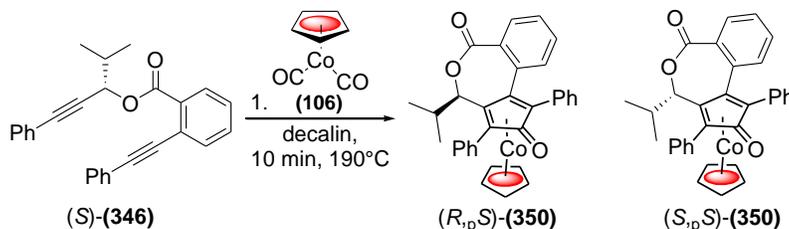
Scheme 74. Synthesis of scalemic metallocenes. [161]

Table 8. Diastereoselective synthesis of cyclopentadienone complexes. [161]

Entry	Diyne	R_1	R_2	R_3	X	Cond. [b]	Yield	Complex	Diastereoselectivity [a]
1	**(343)**	Me	Ph	Ph	CH_2	A	68	**(347)**	4:1
2	**(343)**	Me	Ph	Ph	CH_2	B	69	**(347)**	3.2:1
3	**(344)**	*i*–Pr	Ph	Ph	CH_2	A	50	**(348)**	5:1
4	**(344)**	*i*–Pr	Ph	Ph	CH_2	B	48	**(348)**	5:1
5	**(344)**	*i*–Pr	Ph	Ph	CH_2	C	31	**(348)**	3.5:1
6	**(345)**	Me	Ph	Ph	o–C_6H_4CO	A	19	**(349)**	1:0
7	**(345)**	Me	Ph	Ph	o–C_6H_4CO	B	28	**(349)**	1:0
8	**(346)**	*i*–Pr	Ph	Ph	o–C_6H_4CO	A	33	**(350)**	4:1
9	**(346)**	*i*–Pr	Ph	Ph	o–C_6H_4CO	B	54	**(350)**	3:1
10	**(346)**	*i*–Pr	Ph	Ph	o–C_6H_4CO	C	10	**(350)**	5:1

[a]. Ratio determined by ^1H NMR spectroscopy of crude. [b]. Conditions A: CpCo(CO)$_2$, toluene, 120°C, N$_2$, 12 h. Conditions B: CpCo(CO)$_2$, toluene, 120°C, N$_2$, 18 h. Conditions C: CpCo(CO)$_2$, decalin, 190°C, N$_2$, microwave, 10 min.
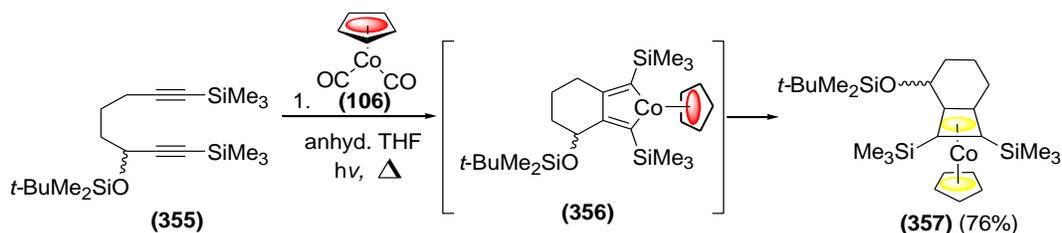
Scheme 75. Synthesis of η^4–cyclobutadiene cobalt complex **(357)** (6:4 fused rings). [162]
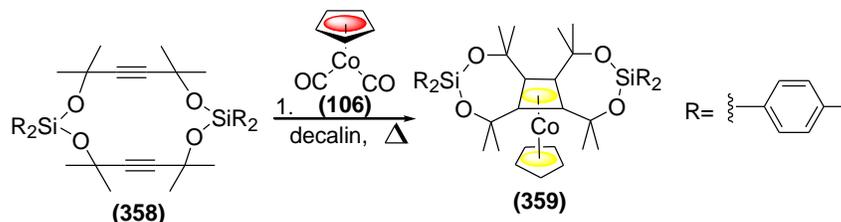
Scheme 76. Synthesis of η^4–cyclobutadiene cobalt complex **(359)**. [163]
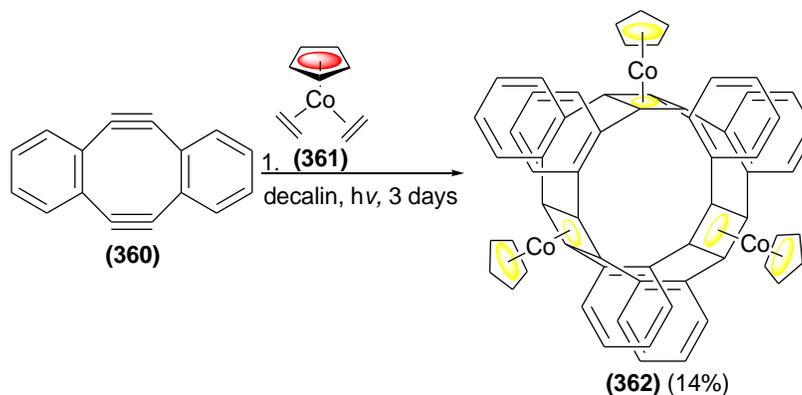
Scheme 77. Synthesis of highly strained η^4–cyclobutadiene cobalt 'belt like' complex. [164]
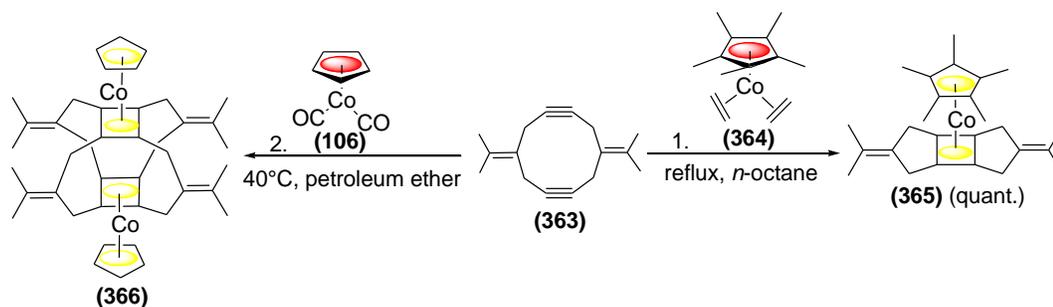
Scheme 78. Intramolecular and intermolecular synthesis of highly strained η^4–cyclobutadiene cobalt complexes. [165]

2.1   Objectives.

The purpose of this research has been to capitalise on this emerging field of diastereoselective complexation using chiral linked diynes and in effect continue the important research done by C. J. Taylor. The objective was to synthesise η^4—cyclobutadiene cobalt metallocenes as these will utilise the positive attributes of a metallocene *i.e.* 18 electron complexes which are robust and soluble in most organic solvents. In addition they will also have enough unique structural merits, like either a smaller η^4—cyclobutadiene unit or a functionalised cyclopentadienyl moiety, to create diversity and serve as an effective 'backbone' for ligands in asymmetric catalysis.

The first objective was to prepare (η^4–tetra–phenylcyclobutadiene)(η^5–cyclopentadienyl)cobalt **(229)** using a range of different sources of cobalt such as; (η^5–cyclopentadienyl)cobalt(dicarbonyl) **(106)**, (η^5–cyclopentadienyl)(1,5–cyclooctadiene)cobalt(I) **(367)**, (η^5–cyclopentadienyl)cobalt(I)*bis*(triphenylphosphine) **(368)** and (η^5–cyclopentadienyl)*bis*(ethylene)cobalt(I) **(361)**. Depending on objective one and the yields obtained, use the procedure on racemic diyne **(343)** initially and then longer chained chiral diyne molecules. Another aim was to develope a method that uses dicobalt octacarbonyl to synthesise chiral diyne **(343)** and to then explore a different route to synthesis of planar chiral cyclopentadienone **(347)**. In the process of investigation of the primary goals also report any novel chemistry as a consequence of persuing the aforementioned.

2.2   Results and Discussion.

Using the procedure reported by M. D. Rausch and R. A. Genetti **(Scheme 79)**, [166], [167] (η^5–cyclopentadienyl)*bis*(carbonyl)cobalt(I) **(106)** was synthesised. The NMR spectrum was consistent with the formulation of **(106)**.
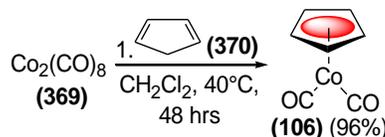
Scheme 79. Synthesis of (η^5–cyclopentadienyl)*bis*(carbonyl)cobalt(I) **(106)**. [166], [167]

(η^5–Cyclopentadienyl)(1,5–cyclooctadiene)cobalt(I) **(367) (Scheme 80)** was synthesised in 40% yield according to the procedure of H. Bonnemann and B. Bogdanovic which reported a 79% yield. [168] The NMR spectrum was consistent with the formulation of **(367)**. The ^{1}H NMR spectrum showed peaks at δ 1.59 ppm (4H, m, 2xCH_2), δ 2.39 ppm (4H, m,

$2xCH_2$), δ 3.47 ppm (5H, s, C_5H_5) and δ 4.58 ppm (4H, s, 4xCH). Furthermore the ^{13}C NMR showed peaks at δ 32.1 ppm (4xCH_2), δ 63.3 ppm (4xCH) and δ 83.8 ppm (η^5–C_5H_5). [169]
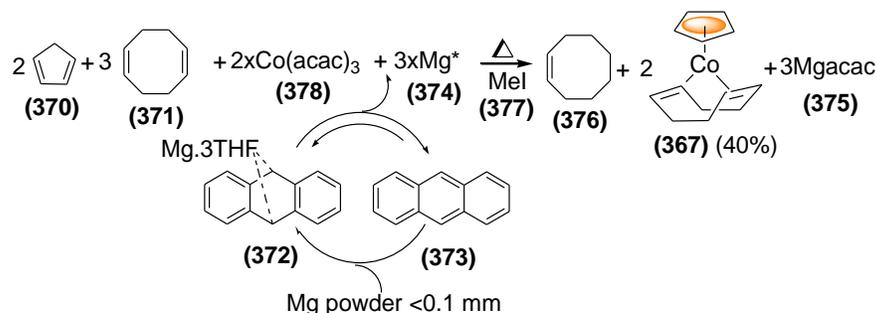
Scheme 80. Synthesis of (η^5–cyclopentadienyl)(1,5–cyclooctadiene)cobalt(I) **(367)**. [168]

Cobalt(I)*tris*(triphenylphosphine) chloride **(100)** which is a precursor needed for the synthesis of (η^5– cyclopentadienyl)cobalt(I)*bis*(triphenylphosphine) **(368)** was synthesised with a yield of 75% according to the literature procedure of Y. Wakatsuki and H. Yamazaki who reported 67% yield. [170] Due to the nature of the compound spectroscopic evidence was not obtained. However a melting point was taken of 135–139°C (dec) **(Scheme 81)**.
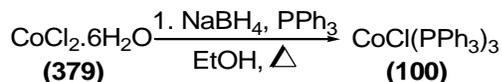
Scheme 81. Synthesis of cobalt(I)*tris*(triphenylphosphine) chloride **(100)**. [170]

The attempted synthesis of (η^5–cyclopentadienyl)*bis*(ethylene)cobalt(I) **(361)** was unsuccessful although the procedure reported by K. Jonas, E. Deffense and D. Habermann was carefully repeated. [171]

The stoiciometric sources of cobalt that were initially screened to make (η^5–cyclopentadienyl)(η^4– tetraphenylcyclobutadiene)cobalt **(229)**, *in situ* generated **(368)** using **(100)** afforded an 83% yield of **(229)** after refluxing in toluene for 5 hours. This yield was similar to the literature value reported [170] which gave 84% yield, m.p. 193–194°C (decomp.). The stoiciometric reagent (η^5–cyclopentadienyl)(cyclooctadiene)cobalt(I) **(367)** when heated to reflux in toluene for 24 hours afforded a low yield of only 12%. However when the solvent was changed to decalin and heated to reflux for 24 hours a 40% overall yield was obtained. This was reasoned to be as a consequence of more energy required for ligand dissociation. Finally the reagent (η^5–cyclopentadienyl)*bis*(carbonyl)cobalt(I) **(106)** under photo irradiation and prolonged thermal heating (24 hours) gave **(229)** in 81% yield and (η^5–cyclopentadienyl)(η^4– tetraphenylcyclopentadienone)cobalt **(381)** in 11% yield. The latter reaction was particularly interesting as heating alone at the same temperature for 24 hours gave a yield of 52% **(229)** and 10% **(381)** **(Scheme 82)**. The yield appeared to be consistent with the report of M. D. Rausch and R. A. Genetti [167] who obtained **(229)** 46% and **(381)** 10%.
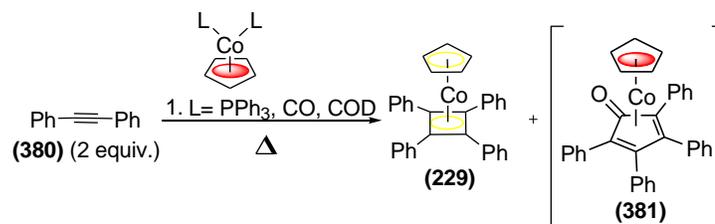
Scheme 82. Synthesis of (η⁵–cyclopentadienyl)(tetraphenylcyclobutadiene)cobalt **(229)** and (η⁵–cyclopentadienyl) (tetraphenylcyclopentadienone)cobalt **(381)**.

The mechanism for the formation of both types of metallocenes illustrated in **Scheme 82** is shown in **Figure 23**. The identities of both **(229)** and **(381)** were confirmed by the spectroscopic evidence previously reported for the metallocenes. Characteristic features which distinguished **(229)** from **(381)** were **(229)** is a bright yellow non polar metallocene. The ^{1}H NMR spectrum shows a single peak at δ 4.62 ppm (5H, s, C_5H_5) and the ^{13}C NMR spectrum shows a peak at δ 83.3 ppm (C_5H_5). Whereas **(381)** is a bright red metallocene that is very polar due to the presence of a carbonyl functionality the ^{1}H NMR spectrum gave a singlet peak at δ 4.63 ppm (5H, s, C_5H_5). Furthermore the infrared spectrum showd a strong stretch at 1581 cm^{-1}(C=O) and the ^{13}C NMR spectrum shows a carbonyl peak at δ159.0 ppm.
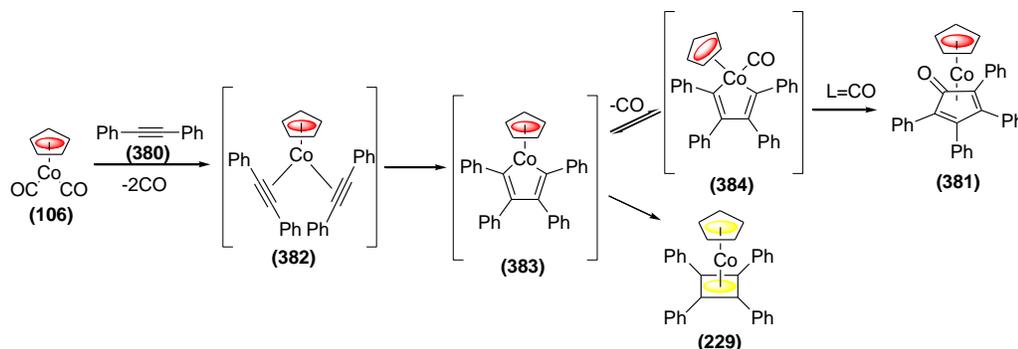
Figure 23. Mechanism for the insertion of CO and divergent metallocene synthesis.

2.3 Cobalt Mediated Diastereoselective Synthesis of Organometallics *via* Exploitation of the Dynamic Behaviour of Dicobalt Hexacarbonyl Propargyl Cations.

This chapter of the thesis discusses how dicobalt octacarbonyl was used to synthesise a known planar chiral cyclopentadienone metallocene with some control of diastereoselectivity. This chapter will also present the initial results in the unexpected discovery of a dynamic kinetic resolution of dicobalt hexacarbonyl propargyl cations which was as a consequence of developing a method for the synthesis of planar chiral η⁴–cyclobutadienes metallocenes.

It was evident from the preliminary screening of cabalt sources that (η⁵–cyclopentadienyl)*bis*(carbonyl)cobalt(I) **(106)** was a likely candidate to synthesise planar chiral η⁴–cyclobutadienes. The added benefit of this method was the utility of its precursor reagent dicobalt octacarbonyl which would allow access to chiral diynes using the Nicholas reaction [172], [173] **(Scheme 83)** which was not investigated at all by C. J. Taylor. The racemic secondary terminal propargylic alcohol 4–phenyl–but–3–yn–2–ol **(391)** was synthesised in two steps in 98% yield. 4–Phenyl–but–3–yn–2–ol **(391)** was then treated with one equivalent of dicobalt octacarbonyl, this gave a two metal centered propargylic alcohol **(392)** in 95% yield **(Scheme 84).** The identity of this compound was confirmed using ^{1}H and ^{13}C NMR spectroscopy and compared

against the spectroscopic data that was reported in the literature. [174] Characteristic downfield shifts were apparent for the CH_3 (doublets) from δ 1.54 to δ 1.61 ppm and δ 4.76 to δ 5.27 ppm (CH) upon complexation. Furthermore, FT–IR spectroscopy showed a stretch at 1709 cm^{-1} for carbonyl functional group.
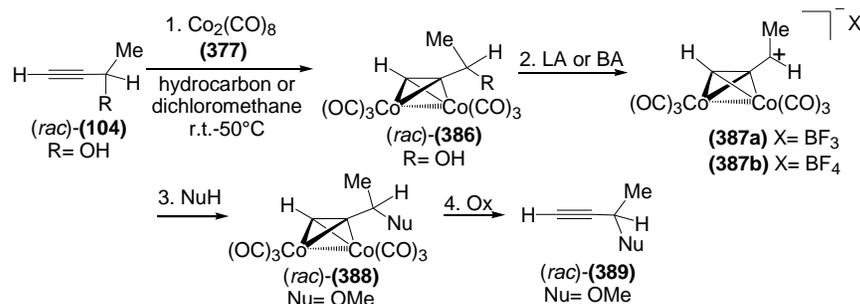
LA= Lewis acid *e.g.* BF$_3$ OEt$_2$ **(385a)** or BA= Brønsted acid HBF$_4$ **(385b)**
NuH= HOMe, Nu= OMe, Ox= oxidant *e.g.* Ce(SO$_4$)$_2$, (NH$_4$)$_2$Ce(NO$_3$)$_6$, X= counter ion

Scheme 83. Illustrates a general method for the Nicholas reaction. [172], [173]
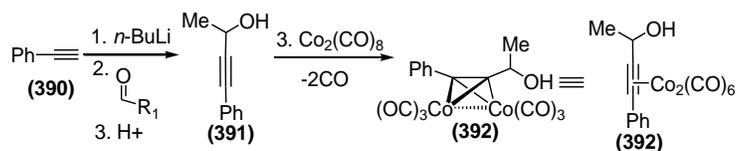
Scheme 84. Synthesis of complexed *rac*–propagylic alcohol **(392)**. [174]

Complex **(392)** was treated with a Lewis acid and then quenched at a low temperature with a propargyl alcohol. This gave complex **(393)** in 68% yield **(Scheme 85, Figure 24)**. The ^{1}H NMR spectrum showed coupling across three bonds between CH and CH_3 group {δ1.59 ppm (3H, d, *J* 6.2 Hz, CH_3) and δ 5.15 ppm (1H, q, *J* 6.2 Hz, CH)}. It was also evident from the ^{1}H NMR that there was long range acetylenic coupling over four bonds of *J* 2.7 Hz between acetylene proton at δ 2.46 and the diastereotopic OCH_2 to give two signals centred at δ 4.34 ppm. Mass spectrometry was ineffective at establishing an intact molecular ion even though a soft ionisation technique was used (fast atom bombardment). FT–IR supported the presence of the dicobalt hexacarbonyl protecting group with a stretch at 1612 cm^{-1} for C=O ligands. The ^{13}C NMR spectrum supported the identity of **(393)** with 12 peaks for the complex and a characteristic peak at δ 74.4 ppm (CHOH) downfield compared to when it is unprotected which appears at δ 64.7 ppm (CHOH).

In this reaction complex **(395)** was isolated as a single diastereoisomer by–product containing two stereogenic centres with a yield of 15% **(Scheme 85)**. The ^{1}H NMR spectrum showed characteristic long range acetylenic coupling between 14–CH and 12–CH_2. The OCHH^1 is observed as two mutually coupled doublets (*J* 16.3 Hz) at δ 4.30 and δ 4.36 each of which shows a doublet coupling (*J* 2.5 Hz) to the alkyne proton at δ 2.50 ppm. The diastereotopic methylene linker 5–CH_2 gives two signals at different chemical shifts as each proton is split by the neighbouring protons at 3–CH and 7–CH at δ 1.86 ppm (1H, ddd, *J* 13.6, 1.7 Hz, CH_2), δ 2.29 ppm (1H, ddd, *J* 13.6, 1.7 Hz, CH_2) (only two coupling constants were distinguishable, from the three expected). The proton 3–CH is a multiplet {δ 3.71 ppm (1H, m, CH)}. Another important coupling that supports the identity of this complex is a doublet of doublet splitting at δ 5.17 ppm (1H,

dd, *J* 16.3, 1.7 Hz, C*H*) for of 7–C*H* split by the non–equivalent protons at 5–C*H*$_2$. The ^{13}C NMR spectrum supported the structure as 21 types of carbon environments could be accounted for as peaks. Furthermore, elemental analysis for C$_{35}$H$_{20}$Co$_4$O$_{13}$, found; C, 47.53%, H, 2.36% from an expected value of C, 47.54% and H, 2.28%. ; FT–IR (thin film) also supported double complexation with a stretch at 1575 cm^{-1} (C=O functional group).
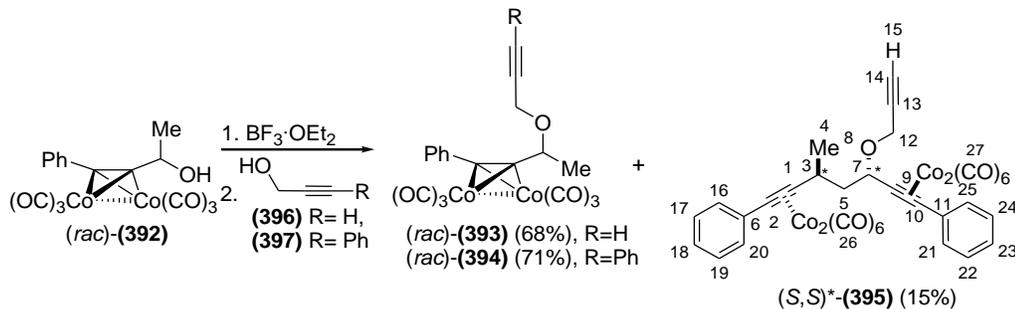
Scheme 85. Synthesis of complexed dicobalthexacarbonyl ether diynes.
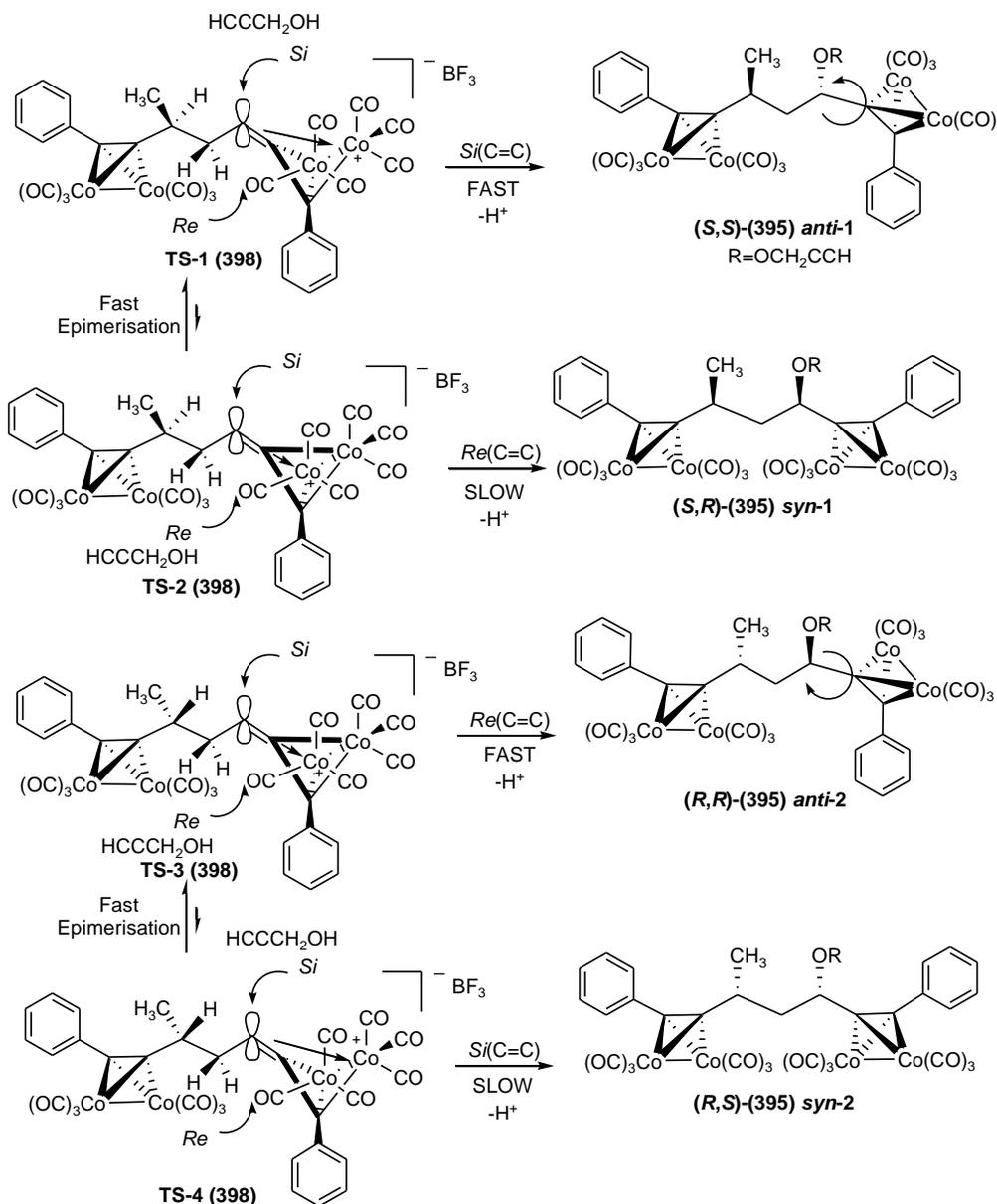
Figure 24. Model illustrating *syn/ anti* diastereoselectivity of **(395)**.

The origins of *syn/anti* diastereoselectivity which leads to four diastereoisomers can be rationalised by considering the stereo–electronic and orbital interactions between the reactant species in the transition state **(Figure 24)**. The **TS–1** and **TS–3** is postulated to be the more stable intermediate as a consequence of epimerisation *i.e.* **TS–2** to **TS–1** and **TS–4** to **TS–3** allowing a favourable approach by the nucleophile. As a result of anchimeric assistance by the neighbouring cobalt cluster stabilised metal fragment there is retention in configuration. The sp^2 hybridised carbenium ion intermediate takes a trigonal planar geometry allowing either the *Re* or *Si* face to be attacked depending on the configuration of the first stereogenic centre by the nucleophile. Thus this gives the *anti* diastereoisomers (*S,S*)–**(395)** and (*R,R*)–**(395)** and hence only one set of signals is detected by spectrometry.

The reagent 3–phenylprop–2–yn–1–ol was found to give a better yield of 71% for **(394) (Scheme 85)**. The identity of this compound could only be confirmed using ^{1}H, ^{13}C and FT–IR spectroscopy. Several ionisation technique were tried but were ineffective in obtaining a molecular ion. The ^{1}H NMR spectrum showed a doublet at δ1.62 ppm which integrated for three protons and was coupling with the C*H* group as there was a clear quartet splitting pattern with a ^3J 5.9 Hz. Moreover, a diastereotopic C*H$_2$* was detected at δ 4.51 and δ 4.54 ppm which had a coupling constant *J* 16.0 Hz for each doublet. The ^{13}C NMR spectrum also supported the identity with 8 carbon peaks in the aromatic region. The identity of this compound was also indirectly confirmed when it was deprotected with an oxidant to give a chiral ether diyne which was a known compound.

Dicobalt hexacarbonyl protected diyne **(394)** was used in a one–pot procedure where it was heated to reflux for 18 hours in toluene with 2 equivalents of cracked cyclopentadiene and gave a 24% yield of planar chiral metallocenes **(347)** with an initial diastereomeric ratio of 3:2 after isolation by short filtration through a sinter. Silica gel column chromatography was only able to enrich the major isomer partially to give a diastereomeric ratio of 4:1 (1:99 methanol/hexane elutant) **(Scheme 86)**. The identity of the metallocenes was confirmed and found to be consistent with the major peaks in both ^{1}H and ^{13}C NMR spectra reported by C. J. Taylor. [161] For example, the ^{1}H NMR spectrum showed signals at δ 1.36 ppm (3H, d, *J* 6.7 Hz, major–C*H$_3$*), δ 4.58 ppm (5H, s, major–C$_5$H$_5$) and δ 1.75 ppm (3H, d, *J* 6.2 Hz, minor–C*H$_3$*), δ 4.73 ppm (5H, s, minor–C$_5$H$_5$). The ^{13}C NMR spectrum showed δ 84.4 ppm (major–C$_5$H$_5$) and δ 83.9 ppm (minor–C$_5$H$_5$). [161] No η^4–cyclobutadiene complexes were observed. The significance of this reaction was that an alternative mechanism was probable that initially goes *via* a Pauson Khand product as opposed to a metallocyclopentadiene intermediate such as that shown for **(383)** in **Figure 23**.
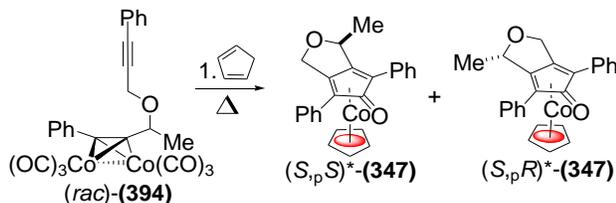
Scheme 86. Diastereoselective synthesis of planar chiral metallocenes of **(347)**.

It was reasoned the desired η4–cyclobutadiene complex would contain fused 5:4 rings, and ring strain may be promoting CO insertion and formation of metallocenes **(347)**. Thus longer diynes were synthesised on the premise that these would result in less strained products on complexation **(Figure 25)**.

165°   140°   150°
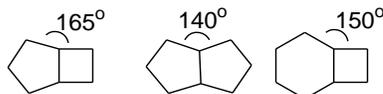
Figure 25. Example of 5:4, 5:5 and 6:4 ring systems.

Treatment of complexed propargylic alcohols **(392)**, **(386)** with four equivalents of the Lewis acid boron trifluoride followed by quenching with propargyl alcohols but–3–yn–1–ol **(399)** or 4–phenylbut–3–yn–2–ol **(406)** gave unexpected and interesting results. Reaction of **(392)** or **(386)** with but–3–yn–1–ol **(399)** gave **(400)** and **(401)** respectively, the former in higher yield. This is anticipated to be because of greater anchimeric assistance of the metal fragment upon ionisation. This allows better shielding of the endo face by fixation of π–π and d–π orbitals which consequently lead to a double inversion and retention of configuration.

Addition of three equivalents of cerium ammonium nitrate to **(400)** gave a yield of 54% for **(404)**. Oxidation of the protected complex **(401)** was followed by thin layer chromatography, the one electron change in the redox level of Ce(IV) to Ce(III) and consumption of dicobalt hexacarbonyl resulted in a clear solution at the end of the reaction. Sonogashira cross coupling of **(404)** gave **(405)** also in a good yield (99%). Which was better then demetallation which gives a 70% yield. Cross coupling with the protected diyne **(400)** however resulted in poorer yields of 31% for **(402)** and 56% for **(403)** when **(401)** is used respectively **(Scheme 87)**.
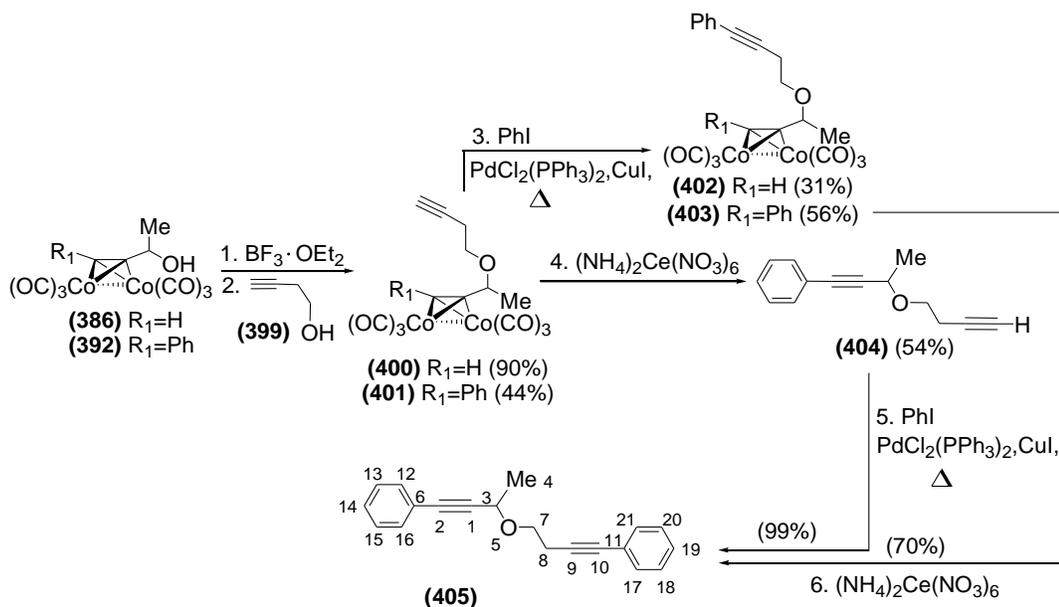
Scheme 87. Synthesis of longer chained diynes.

FT–IR, ^{1}H and ^{13}C NMR spectroscopy were mainly used to characterise the dicobalt hexacarbonyl protected complexes. A more complete characterisation was made for **(405)** which confirmed the synthesis of the precursor

complexes. The ^{1}H NMR spectrum for **(405)** gave a doublet and a short range coupling constant of ^3J 6.7 Hz between 4–CH_3 at δ 1.47 ppm and the quartet of 3–CH at δ 4.41 ppm. With respect to the longer chain linker 8–CH_2 at δ 2.67 ppm shows a triplet splitting pattern with a coupling constant of J 8.1 Hz. Both the diastereotopic 7–CH_2 have different chemical shifts *i.e.* δ 3.62 ppm (1H, dt, J 8.1, 2.7 Hz, 7–CH_2) and δ 3.90 ppm (1H, dt, J 8.1, 2.7 Hz, 7–CH_2). The ^{13}C NMR spectrum shows 16 peaks consistent with the number of carbon environments. High resolution mass spectrometry using chemical ionisation gave a molecular ion for $C_{20}H_{22}ON$;{ $[M+NH_4]^+$} which found 292.1697 from the required value of 292.1696. FT–IR also showed some typical absorption bands expected for this compound 3078 (aliphatic stretch), 2978 (aliphatic stretch), 2866 (C≡C stretch), 1599 and 1105 cm^{-1} (ether stretch).

An alternative mode of nucleophilic addition took place following treatment with a Lewis acid boron trifluoride and quenching with a longer chained propargyl alcohol. This reaction gave **(407)** in 79% yield and a single diastereoisomer of (*S,S*)*–**(408)** in 3% yield **(Scheme 88)**.
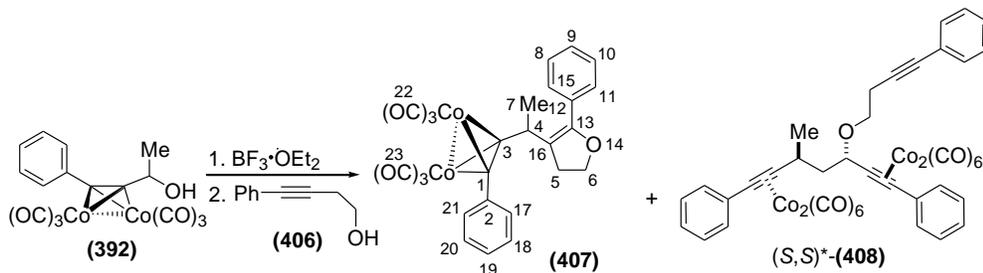
Scheme 88. Alternative mode of nucleophilic attack.

The identity of complex **(407)** was confirmed using ^{1}H NMR spectroscopy which showed a doublet at δ 1.62 ppm that integrated for three protons with a coupling constant of J 8.1 Hz (7–CH_3), this was the same for the quartet at δ 4.51 ppm which integrated for one proton. The 5–CH_2 gave a 1H multiplet at δ 2.63 ppm, at δ 2.91 ppm a ^{1}H doublet of triplet was present with coupling constants of 10.8 Hz and 2.7 Hz. This bigger coupling constant was the same for one of the protons of 6–CH_2 at δ 4.25 ppm. The ^{13}C NMR spectrum showed 16 carbon environments. Low resolution mass spectrometry (pFAB) in the positive mode gave a molecular ion minus three CO ligands for $C_{23}H_{18}Co_2O_4$ $[M–3CO]^+$= 476.1. **Figure 26** proposes a mechanism for its assembly.

Complex (*S,S*)*–**(408)** showed similarities with complex (*S,S*)*–**(395)**. Notable differences which helped identify this complex were the two signals that integrated for two protons at δ 2.72 and δ 3.75 ppm. The doublet of doublet splitting at δ 4.96 ppm was found to couple with both diastereotopic methylene protons at δ 1.85 and δ 2.34 ppm which gave J 1.2 Hz. The increased number of integrated protons in the ^{1}H NMR and an increase in the number of signals for the carbon environments supported this structure. Moreover, to support the double complexation two signals one at δ 199.3 ppm and the other at δ 199.7 ppm were assigned to the carbon monoxide ligands which were in different chemical environment. FT–IR spectroscopy also showed a typical stretch at 1605 cm^{-1} for the CO functional group and the elemental analysis was satisfactory.
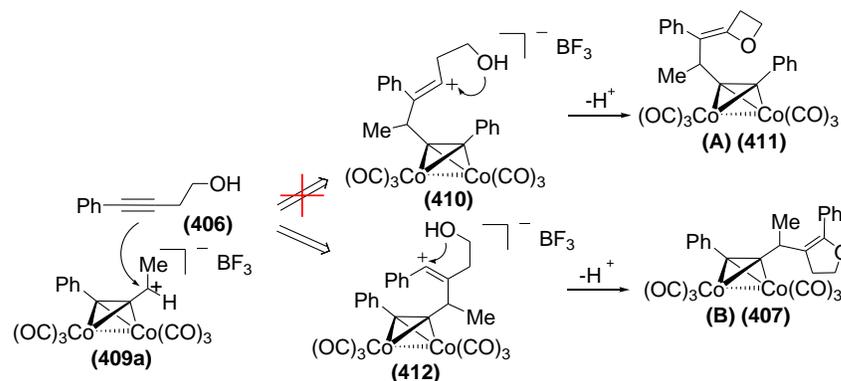
Figure 26. Proposal for the alternative more of nucleophilic attack.

Diyne **(405)** was investigated as a potential candidate for diastereoselective planar chiral metallocene synthesis by reacting exactly 2.1 equivalents with (η5–cyclopentadienyl)*bis*(carbonyl)cobalt(I) **(106).** Using the experimental procedure and setup reported by P. Eckenberg and U. Groth that gave **(357) (Scheme 75)**, [162] *i.e.* 60°C, photo irradiation, anhydrous tetrahydrofuran this reaction was replicated. Careful monitoring of the reaction using thin layer chromatography indicated decomposition of the chiral diyne. Staining the TLC using an iodine stain did not enhance any faint yellow spots. Low resolution mass spectrometry (LCMS) and a crude NMR after removal of volatile components *in vacuo* (after 48 hours) did not show signs of desired metallocene formation **(Scheme 89)**. The same observation was made for diynes **(343)** and **(405)** using (η5–cyclopentadienyl)(1,5–cyclooctadiene)cobalt(I) **(367)** **(Scheme 90)**. A hypothesis was made that actually the extended diyne itself maybe preventing the complexation process. Previously successful with the protected diyne **(394)** in the synthesis of planar chiral metallocenes **(347)** using diyne **(403)** the reaction was repeated using the same conditions **(Scheme 91)**, the reaction did not give any metallocenes which supported the results of the reactions illustrated in **Scheme 89, 90**.
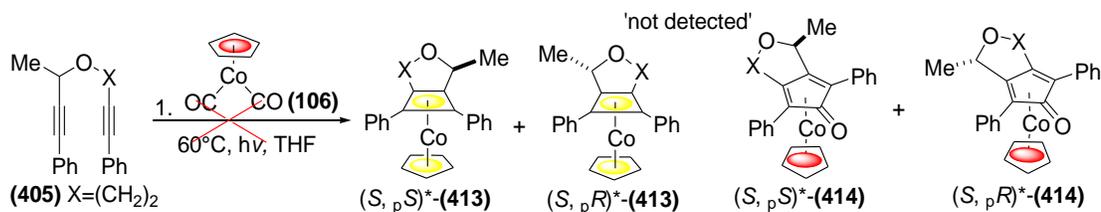
Scheme 89. Attempted diastereoselective synthesis of **(413)** and **(414)**.
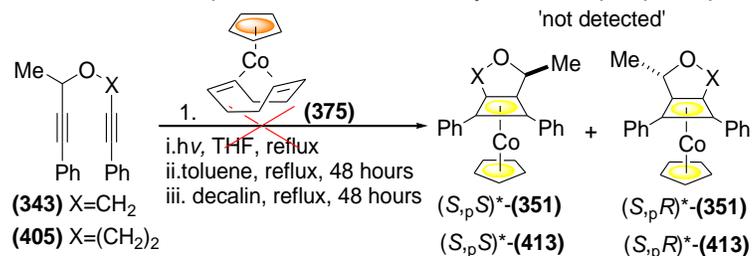
Scheme 90. Attempted diastereoselective synthesis of **(351)** and **(413)**.
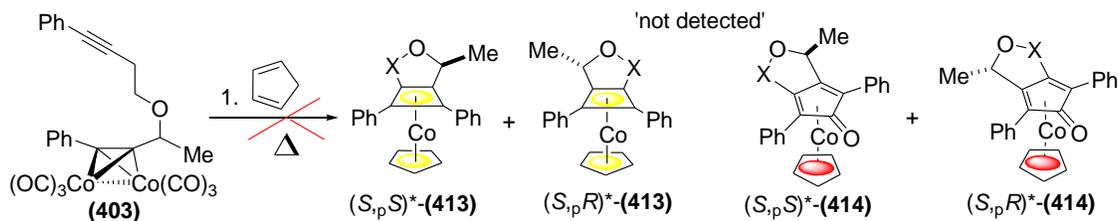
Scheme 91. Attempted diastereoselective synthesis of **(413)** and **(414)**.

In summary, chiral diynes **(343)**, **(403)** and **(405)** were reacted with stoiciometric amounts of sources of cobalt. Under thermal and photo irradiation conditions no distinctly yellow spots were observed. Under thermal conditions alone, *i.e.* using anhydrous toluene or decalin and heating at reflux for more than 12 hours, gave coloured spots for diyne **(343)** with (η^5–cyclopentadienyl)(1,5–cyclooctadiene)cobalt(I) **(367)**. Investigation of possible metallocene type structures was extremely difficult with respect to purification. Spectroscopic techniques were very ambiguous. For example, the ^{1}H NMR spectra had multiple peaks that could be attributed to the η^5–cyclopentadienyl group in a cyclobutadiene framework.

In the third chapter the investigation into diastereoselective complexation will be discussed using (η^5–cyclopentadienyl)cobalt(I)*bis*(triphenylphosphine) **(368)**. This chapter will now convey some of the interesting chemistry which was discovered as a consequence of trying to synthesise chiral diynes using the Nicholas reaction.

The presence of complex (*S,S*)*–**(395)** **(Scheme 85)** and (*S,S*)*–**(408)** **(Scheme 88)** in what was anticipated to be a straight forward Nicholas reaction was of interest. Retro synthetic analysis of these complexes **(Figure 27)** allowed a hypothesis to be made explaining its assembly. Moreover it was thought chirality from C3 was being relayed across two bonds to carbon C5 (a model is proposed in **Figure 28**). The implications for such a phenomenon taking place was perceived to be useful as a method to create templates that could be used for the Pauson Khand reaction [175] amongst others to make functionalised benzene derivatives or chiral bicyclic frameworks.
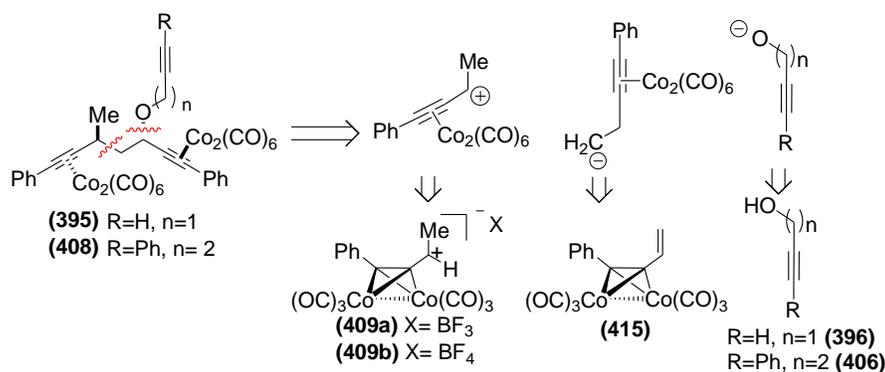
Figure 27. Retro synthetic analysis of (*S,S*)*–**(395)** and (*S,S*)*–**(408)**.
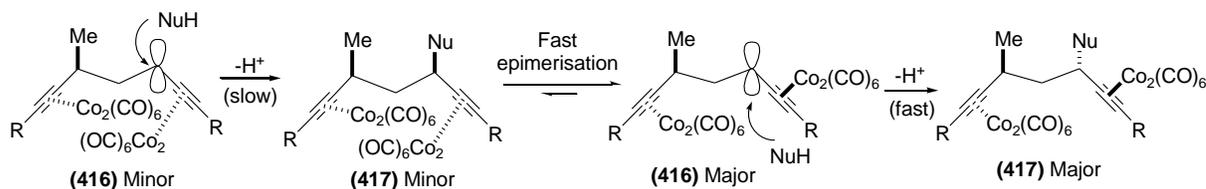
Figure 28. A possible model for dynamic kinetic resolution and internal asymmetric induction.

It was hypothesised that treatment of the complexed propargylic alcohol **(392)** with either a Lewis acid (BF$_3$·OEt$_2$) or Brønsted acid resulted in the formation of a dinuclear organocobalt cationic cluster complex which to some extent underwent an elimination reaction thus giving a dicobalt hexacarbonyl protected enyne complex. As the nucleophile propargyl alcohol was added shortly after treatment with the Lewis or Brønsted acid the components for the spontaneous cascade reaction were in place. It was postulated nucleophilic attack by the enyne complex was favoured as opposed to the propargyl alcohol. The element of diastereoselectivity was thought to originate from the unfavourable steric clashes forcing kinetic resolution of the emerging cationic centre on carbon C5 by a second nucleophilic attack, this time by the propargyl alcohol adding *anti* relative to the stereogenic centre on carbon C3 **(Figure 28)**.

Several attempts at synthesis were needed to test this hypothesis and to achieve control in repetition of this reaction. One objective was to find another alternative to boron triflouride such as fluoroboric acid (HBF$_4$) as a salt of the cationic dinuclear cluster complex could be stored. Addition of six equivalents of the Brønsted acid to **(392)** gave **(418)** with a combined yield of diastereoisomers of 13% and a theoretical diastereomeric ratio of (S,S)* 15: (S,R)* 1 in favour of the presumed *anti* diastereoisomer. Complex **(419)** was also obtained with a 17% yield **(Scheme 92)**. The ^{1}H NMR spectrum supported the identity of **(418)**. As the characteristic chemical shifts and splitting patterns was present with respect to (S,S)*–**(418)**, for example the major isomer gave signals at δ 1.24 (3H, t, J 6.9 Hz, 12–CH_3) showing coupling with the signal at δ 3.60 ppm (2H, q, J 6.9 Hz, 11–CH_2). At δ 1.50 a J 6.7 Hz coupling of 3–CH_3 with the signal at δ 3.86 ppm which was expected to be ddq appeared as a *app* dq J 6.7 Hz. The diastereotopic methylene protons at δ 1.82 and δ 2.28 ppm (1H, ddd, J 13.1, 10.9, 2.0 Hz, 4–CH_2) were found to couple with the signal at δ 4.80 ppm (1H, dd, J 10.9, 2.0 Hz, 6–CH). The ^{13}C NMR spectrum indicated a double complexation giving signals at δ 199.4 ppm (25–CO) and δ 199.8 ppm (24–CO). High resolution mass spectrometry also supported the structure as for C$_{34}$H$_{20}$Co$_4$O$_{13}$ [M–2H]$^+$ = found 872.9058 requires 872.8900.
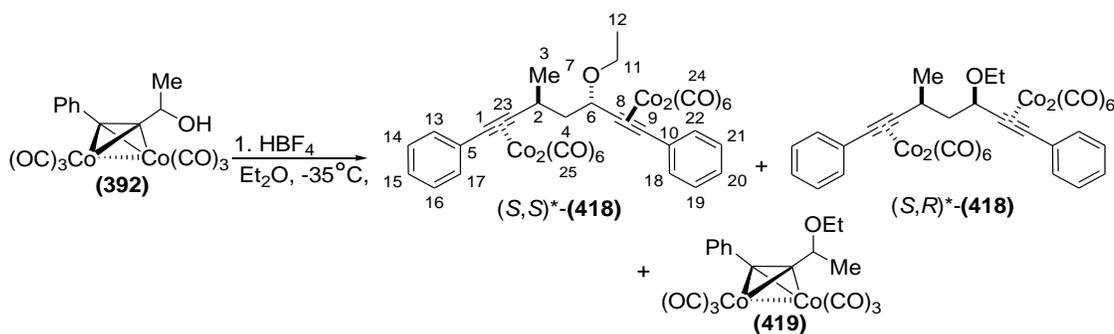
Scheme 92. Products isolated from using an excess of Brønsted acid HBF$_4$.

Eventually, it was established that a dropwise addition of fluoroboric acid (HBF$_4$) to **(392)** in a minimum amount of solvent (diethyl ether) keeping the reaction temperature at –35°C promoted precipitation of the tetrafluoroborate salt **(409b)** (95%) **(Scheme 93)**. The synthesis of this cationic complex **(409b)** was also accomplished with (3–methoxybut–1–ynyl)benzene 1,2–dicobalt hexacarbonyl **(420)**. However, it was found to take much longer to obtain the precipitate ~1.5–2 hours relative to **(392)**. This observation was found to agree with the literature. [174] Moreover to support the identity of **(409b)** and charge delocalisation comes from an increase in the IR absorption frequencies of the carbonyl ligands present on the cobalt cation. An increase of between 40–60 cm^{-1} is consistent with a greater C–O bonding as a result of less d(Co)→π*(CO) donation in the electron deficient cobalt cations. Moreover, CO ligands also show some degree of shielding consistent with high levels of charge dispersal.

In order to develop a reliable method to synthesise enyne complex **(415)**, several bases were screened which included triethylamine, lithium diisopropylamide (LDA) and 1,8–diazabicyclo[5.4.0]undec–7–ene (DBU). Two equivalents of the latter 1,8–diazabicyclo[5.4.0]undec–7–ene (DBU) was found to promote the formation of **(415)** in 82% yield when left to stir for 72 hours **(Scheme 93)**. Alternatively 1 equiv. of trifluoroacetic acid was found to also give a 45% yield of **(415)**. The structure was confirmed by considering the coupling constants for the diastereotopic =CH_2 at δ 5.57 ppm (1H, d, ^3J 10.1 Hz, *cis*–CH) and δ 5.71 ppm (1H, d, ^3J 16.6 Hz, *trans*–CH) and the deshielded HC= at δ 7.07 ppm (1H, dd, ^3J 16.6, 10.1 Hz, CH).
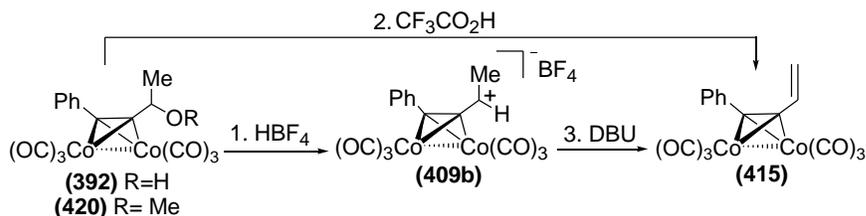
Scheme 93. Synthesis of tetrafluoro borate complex **(409)** 'Nicholas cation' and complexed enyne **(415)**.

In a controlled reaction (*S,S*)*–**(395)** was synthesised in 47% yield showing a diastereomeric ratio of (*S,S*)* 1: (*S,R*)* 0 *i.e.* the minor diastereoisomer could not be detected by ^{1}H NMR spectroscopy. To establish if the reaction was significantly influenced by the temperature, diethylamine and methanol were used to quench the reaction at –35°C or after allowing the reaction mixture to warm to room temperature and then adding the nucleophile **(Table 9)**.

Table 9. Investigation of dynamic behaviour in dicobalt hexacarbonyl complexed diynes.
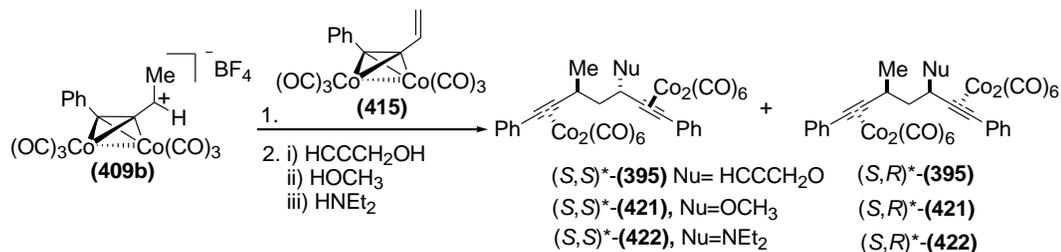
Entry	Complexed Diyne	Nu	Temp.	Brønsted Acid	Diastereoselectivity (*anti*:*syn*) [a]	Yield (%)
1	**(395)**	$HCCCH_2OH$	–35°C	HBF_4	1:0	47
2	**(421)**	MeOH	–35°C	HBF_4	1:0	40
3	**(421)**	MeOH	R.T.	HBF_4	2:3	19
4	**(422)**	$HNEt_2$	–35°C	HBF_4	1:0	37
5	**(422)**	$HNEt_2$	R.T.	HBF_4	4:3	20

[a].Stereochemistry determined by stereochemical correlation studies.

Addition of the nucleophiles at low temperatures revealed the reaction to favour the *anti* diastereoisomer. The selectivity appeared to be slightly reversed in the case of entry 3, **Table 9** when the nucleophile was added at room temperature. The low temperature selectivity could be a result of greater stereoselectivity at low temperature, or could be a result of the configurational stability of the cationic complex, a single diastereoisomer resulting from enyne addition.

The ^1H NMR spectrum was used to calculate the ratio of *anti* and *syn* isomers. With respect to **(421)** a singlet for the methoxy functionality appeared at δ 3.55 ppm (3H, brs, OCH_3) and was attributed to the major isomer when the nucleophile is added at low temperature. The major isomer from the reaction where the nucleophile was added at room temperature gave a signal at δ 3.48 ppm (3H, brs, OCH_3). Low resolution mass spectrometry gave an ion at m/z 776.0 corresponding to ($C_{30}H_{20}Co_4O_{10}$), [M–3CO]$^+$. With respect to **(422)** the major isomer for the low temperature reaction was identified by the two ethyl groups of diethylamine on the NMR spectrum. The major isomer in this case appeared at δ 1.41 ppm (3H, d, *J* 6.4 Hz, CH_3). With the reaction that was quenched at room temperature the minor isomer appeared at δ 1.53 ppm (3H, d, *J* 6.4 Hz, CH_3). Low resolution mass spectrometry gave an ion at m/z 845.0 corresponding to ($C_{34}H_{27}Co_4O_{10}N$), [M–2CO]$^+$.

The reactions illustrated in entry 3 and 5 **(Table 9)** also gave by–products **(Scheme 94)**. For example, in the case of entry 5, in addition to **(422)**, (*E*)–**(424)** was formed in 43% yield as a single double bond isomer, thought to be the (*E*)–isomer based on the coupling constant of ^3J 14.8 Hz and the doublet of quartet splitting pattern and coupling constant for the stereogenic centre at δ 1.57 ppm (3H, d, ^3J 5.4 Hz, CH_3) and δ 4.10 ppm (1H, dq, ^3J 8.1, 5.4 Hz, CH). With respect to **(423)** the diastereoisomers were isolated in a combined yield of 30% with a diastereomeric ratio of 4:1 this

result was assumed to be because the reaction mixture was subjected to an aqueous work up. The identity of **(423)** was confirmed with a high resolution mass spectrum which found 817.8282 from the required value of 817.8117.
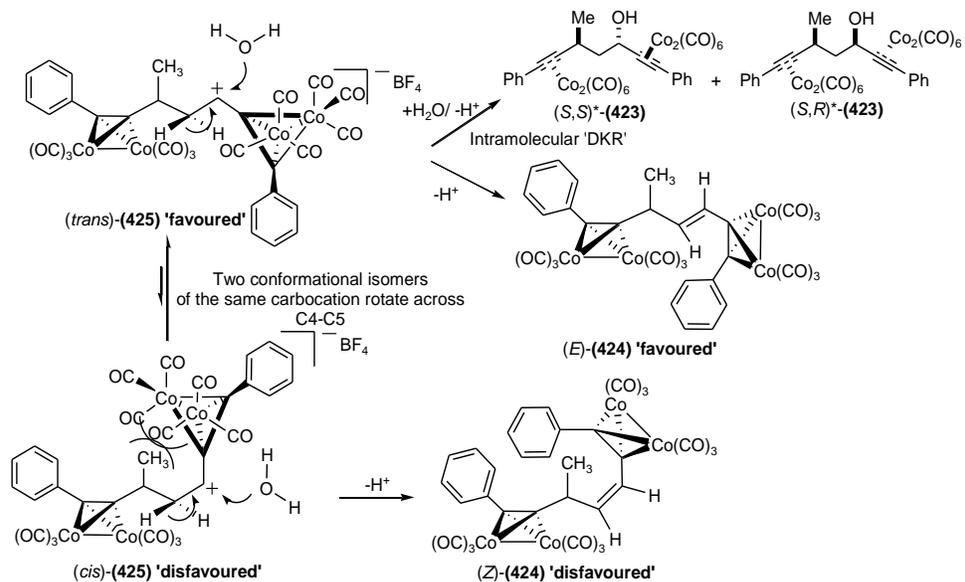
Scheme 94. Proposed mechanism for the synthesis of hydroxyl derivative **(423)** and elimination product **(424)**.

With a theory proposed for how chirality was being relayed from C3 to C5, the aromatic group on the propargylic alcohol was substituted with an *n*–butyl group **(426)** **(Scheme 95)**. Using the general procedure for tetrafluoroborate formation, this reaction was attempted. Careful dropwise addition of the Brønsted acid to **(427)** did not give a solid precipitate but instead a burgundy coloured oil was observed. Thin layer chromatography indicated the presence of new complexes which were not starting material. An aqueous work up followed by column chromatography revealed **(428)** with a yield of 31% and a diastereomeric ratio of 4:1 and **(429)** with a diastereomeric ratio of 6.5: 1 in 10% yield and also **(430)** with a yield of 17%. On the assumption that the model shown in **Figure 27** is followed, and the reaction is taking place under kinetic control in favour of the *anti* diastereoisomer, a comparison can be made which would suggest a net decrease in stereo differentiation when the aromatic groups in the complexed diyne are substituted with an aliphatic group. Where the ethoxy functionality originates from is unclear but thought to be formed from diethyl ether. A comparison could also be made with the hydroxy derivative **(423)** which gave a diastereomeric ratio of 4:1 and **(428)** which also gave a diastereomeric ratio of 4:1 as both were quenched after being warmed up to room temperature the diastereomeric ratio is the same.
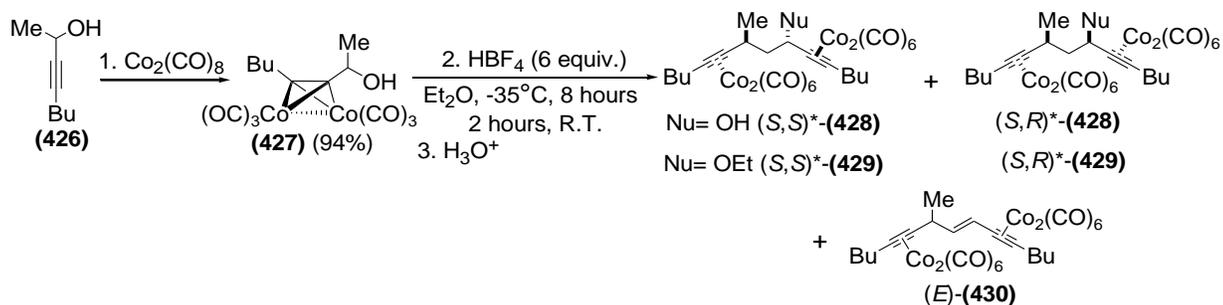
Scheme 95. Products isolated from an unsuccessful borate salt synthesis.

The identity of **(428)** was supported by FT–IR which showed an absorption band at 3351 cm^{-1} which was attributed to the hydroxy functionality. A low resolution mass spectrum gave an ion at m/z 665.9 corresponding to ($C_{23}H_{25}Co_4O_8$), [M–5CO]$^{+}$.

The identity of **(429)** was supported by FT–IR, ^{1}H and ^{13}C NMR spectroscopy. Both elemental analysis and high resolution mass spectrometry were satisfactory. The identity of **(430)** could only be probed by ^{1}H NMR spectroscopy, as the complex was very unstable and showed decomposition in the NMR spectrum. Characteristic features which suggested an (*E*)–configuration was the *J* coupling constants at δ 6.06 ppm (1H, dd, ^3J 14.8 Hz, 8.2 Hz, C*H*) and at δ 6.63 ppm (1H, d, ^3J 14.8 Hz, C*H*).

Esterification of complex **(423)** which initially had a diastereomeric ratio of 4:1 with 1–naphthalenecarboxylic acid gave **(432)** with a combined yield of 82% and a diastereomeric ratio of 14:3 after silica gel column chromatography **(Scheme 96)**. Attempts to crystallise this complex and separate the major diastereoisomer were unsuccessful, a red/brown oil crashed out. The ^{1}H NMR spectrum supported the identity of **(432)** as new signals were present downfield. For example, the major isomer gave signals at δ 7.89 ppm (1H, dd, *J* 7.2, 1.2 Hz, 11–ArC*H*), δ 8.05 ppm (1H, d, *J* 7.2 Hz, 12–ArC*H*), δ 8.32 ppm (1H, dd, *J* 7.4, 1.0 Hz, 10–ArC*H*), δ 9.04 ppm (1H, d, *J* 7.4, 1.0 Hz, 9–ArC*H*). Low resolution mass spectrometry gave a fragment of an ion at 915.9 which found [M–3CO]$^{+}$= 915.9.
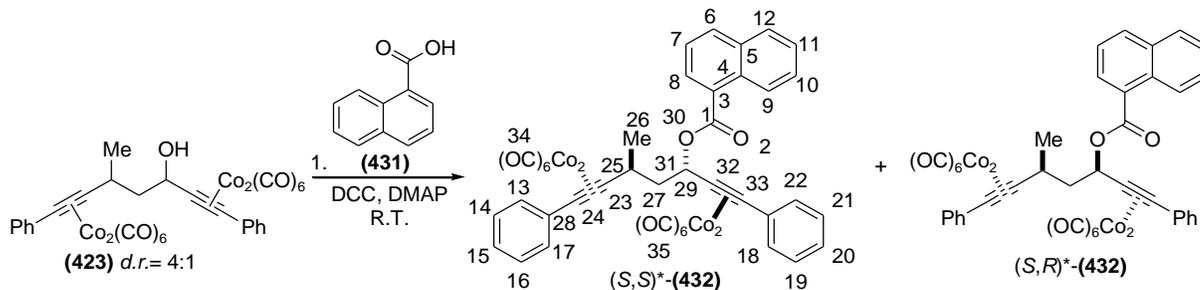
Scheme 96. Functionalisation and preservation of stereochemistry.

Oxidation of the complexed diynes **(423)**, **(421)** (R= Ph) and **(428)** (R= Bu) using cerium ammonium nitrate followed by column chromatography and preparative thin layer chromatography did not separate a single diastereoisomer. Oxidation of the complexed diynes did however preserve to a large extent the same ratio of diastereoisomers when complexed **(Scheme 97)** *i.e.* **(433)** (72%) *d.r.*= 5:1, **(434)** (69%) *d.r.* = 4:1 and **(435)** (99%) *d.r.*= 5:1. Spectroscopic information supported the synthesis of the decomplexed diynes.
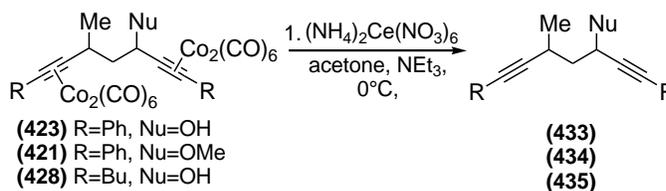
Scheme 97. Decomplexation reaction using six equivalents of oxidising agent $(NH_4)_2Ce(NO_3)_6$.

Complex **(436)** was also isolated in a good yield **(Scheme 98, Figure 29)**. A mechanism is shown in **Figure 31** which describes two possible diastereomeric cations which differ in the relationship they have with the ethylidene group to the carbido carbon (*syn/anti*). **Figure 31** and **32** shows how nucleophilic attack proceeds *anti* to cobalt when adding to the ethylidene ligand. This stereoelectronic control results in the relative generation of one diastereoisomer. Both canonical forms are shown of the cation as it can be considered that the cationic charge is localised on the carbocation or cobalt cation. The latter is a better representation of charge distribution and the fluxional process inherent of the Nicholas cation and is discussed by S. L. Schreiber. [174] By adding the tetrafluoroborate complex **(409b)** to its precursor **(392)** at low temperature and then giving the reaction mixture an aqueous work up resulted in a double stereo differentiation of **(437) (Scheme 98, Figure 30)**. Diastereoselectivity took place intermolecularly, in a dynamic kinetic resolution. Only one diastereoisomer was observed in the ^{1}H NMR spectrum of the product. The relative configurations of **(436)** and **(437)** were determined by X–ray crystallography.
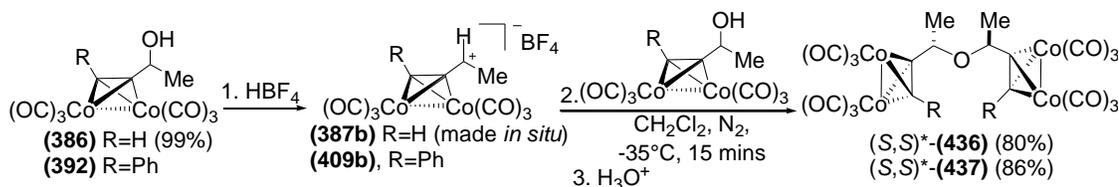
Scheme 98. Intermolecular dynamic kinetic resolution (*S,S*)*–**(436)** and (*S,S*)*–**(437)**.

Both the X–ray crystallography data confirm the complexation of dicobalt hexacarbonyl. For example, with (*S,S*)*–**(436)** The bond length for C(17)–C(18) of 1.337(3) Å suggests the bond length strongly deviates from alkyne bond lengths. Moreover, the bond angle for C(13)–C(14)–C(15) of 143.4218° suggests a bent geometry which is different from a triple bond geometry which would be 180°.
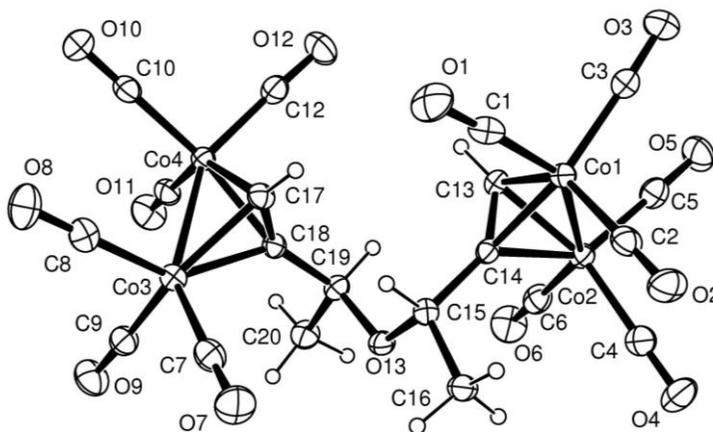
Figure 29. Molecular structure and atom numbering scheme for (*S,S*)*–**(436)** with 50% displacement ellipsoids. Selected bond distances (Å) and angles (°): C(3)–O(3) 1.131(3), Co(3)–Co(4) 2.4776(3), C(15)–O(13) 1.427(2), C(15)–C(16) 1.515(3), C(17)–C(18) 1.337(3), C(19)–O(13) 1.426(2), C(19)–C(20) 1.516(3), C(13)–C(14)–C(15) 143.42(18), C(19)–O(13)–C(15) 116.74(14).
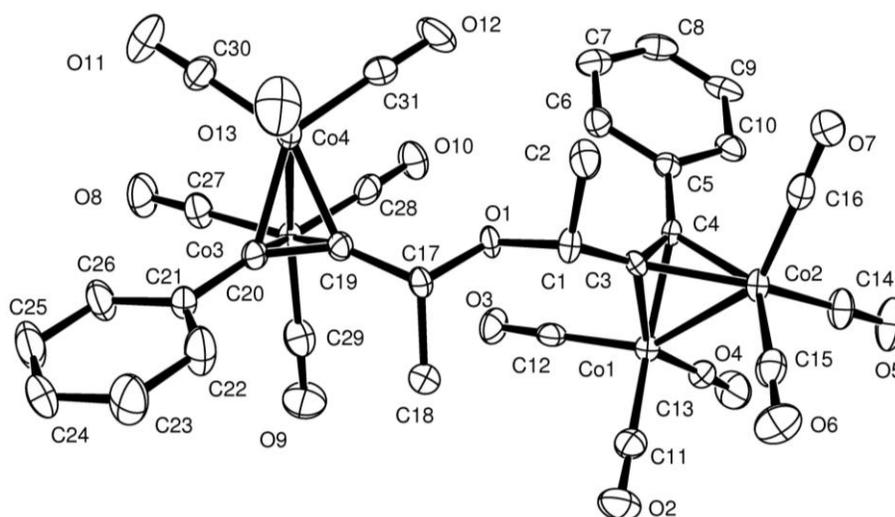
Figure 30. Molecular structure and atom numbering scheme for (*R*,*R*)*–**(437)** with 50% displacement ellipsoids, all H atoms are omitted for clarity. Selected bond distances (Å) and angles (°): Co(1)–Co(2) 2.4685(7), C(3)–C(4) 1.349(5), C(17)–O(1) 1.443(4), C(17)–C(18) 1.528(5), C(31)–O(12) 1.129(5), C(1)–C(3)–Co(1) 133.1(2), O(1)–C(17)–C(18) 110.8(3), C(15)–Co(2)–C(4) 140.36(16).

Dynamic kinetic resolution was also observed to take place using **(427)** forming **(438)**. Only a single diastereoisomer was detectable by ^{1}H NMR spectroscopy. Although very similar to the complexed propargylic alcohol, the product was distinguished from the starting material by the absence of a peak at δ 1.75 ppm corresponding to the hydroxyl functionality. Secondly a shift upfield in the C*H* signal adjacent to oxygen although now integrating for two protons at δ 4.85 ppm (2H, m, C*H*) from δ 4.99 ppm (1H, m, C*H*). Moreover, a low resolution mass spectrum gave an ion at m/z 721.9 corresponding to ($C_{25}H_{26}Co_4O_{10}$), [M–3CO]$^+$ **(Scheme 99)**.
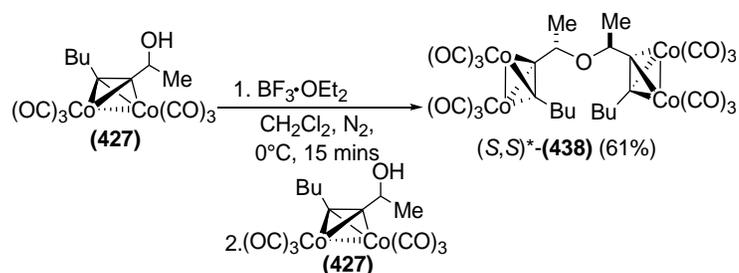
Scheme 99. Dynamic kinetic resolution of (*S*,*S*)*–**(438)**.
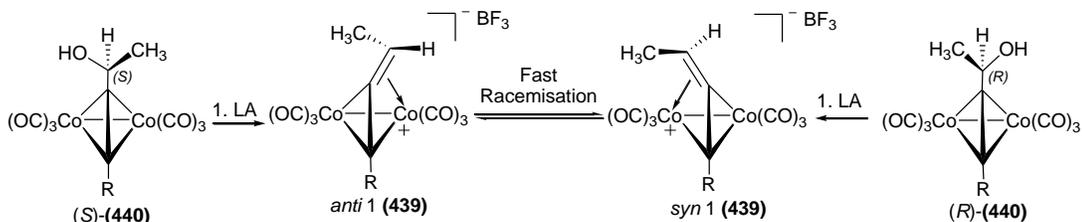
Figure 31. Heterolysis of the carbon–oxygen bond gives diastereomeric cations.
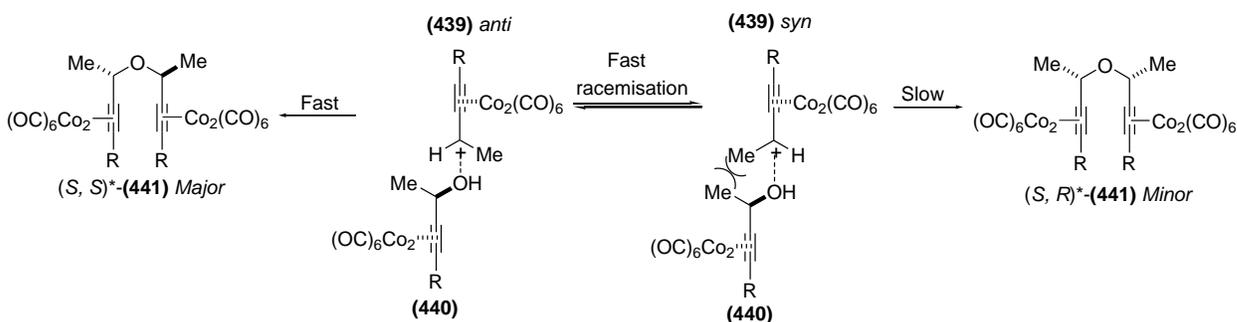
Figure 32. Model for Intermolecular dynamic kinetic resolution.

To determine if chirality could be relayed with a substituent which was not a methyl group (*rac*)–1,3–diphenyl–prop–2–yn–1–ol **(442)** was used. Anticipating solubility could be an issue, anhydrous THF was substituted for anhydrous diethyl ether. An unusual dimerisation of two cobalt–complexed propargyl species took place and gave **(446)** with a yield of 67%, *d.r.*= 12:1 **(Scheme 100)**. The relative stereochemistry of (*S,S*)*–**(446)** was determined by X–ray crystallography **(Figure 33)**. The ^{1}H and ^{13}C NMR spectrum helped to elucidate the diastereomeric ratio. For example, the *meso* isomer gave a signal for C*H* at δ 4.78 ppm and *anti* isomer gave a signal at δ 5.15 ppm. This observation was consistent with respect to the ^{13}C NMR spectrum which showed a signal at δ 54.0 ppm (*S,R**)–C*H* for the *meso* compound and δ 60.5 ppm for the *anti* isomer.
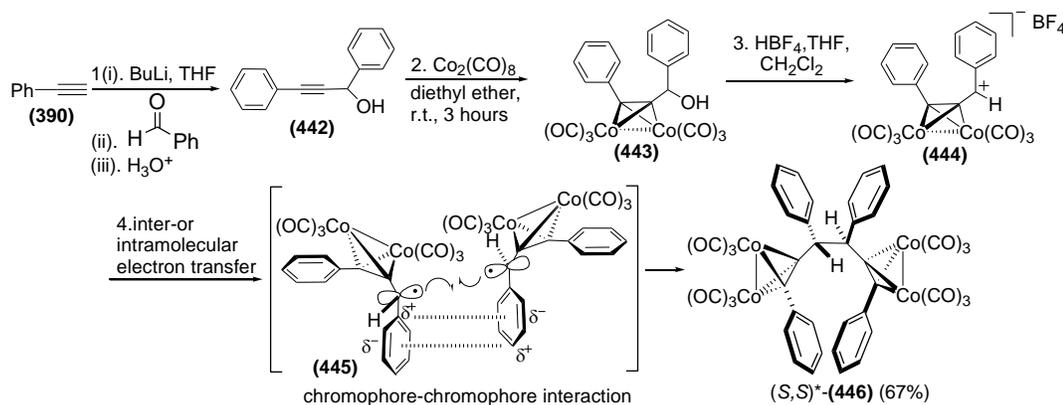
Scheme 100. Synthesis of (*S,S*)*–**(446)**.
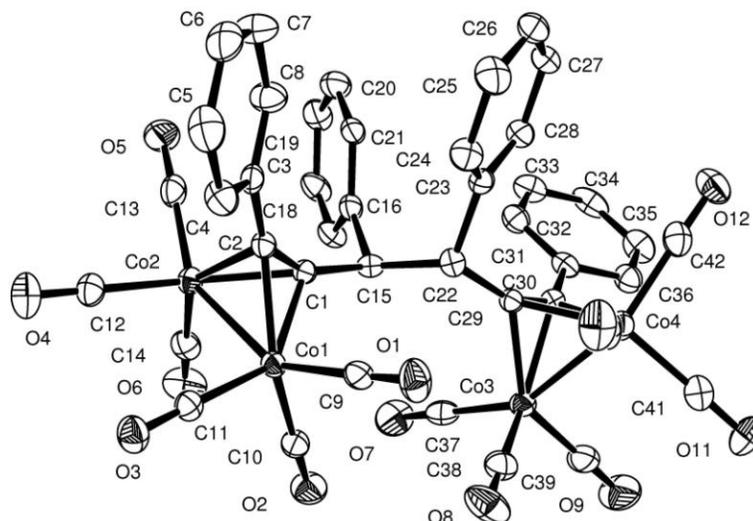
Figure 33. Molecular structure and atom numbering scheme for (*S,S*)*–**(446)** with 50% displacement ellipsoids, all H atoms are omitted for clarity. Selected bond distances (Å) and angles (°): C(1)–C(2) 1.353(5), C(1)–C(15) 1.521(5), C(1)–Co(1) 1.983(4), C(15)–C(22) 1.566(5), C(15)–C(16) 1.535(4), C(22)–C(23) 1.536(4), C(1)–C(15)–C(16) 110.5(3), C(1)–C(15)–C(22) 111.0(3).

A literature search revealed that a very similar reaction was reported by G. G. Melikyan and co workers in 2003 using [1–(4–methoxyphenyl)–prop–2–yn–1–ol]dicobalthexacarbonyl **(448) (Scheme 101)**. [176] It was speculated in this report that the reaction took place because of the electronic and steric parameters of the metal which led to this unusual radical reaction. The major isomer was (*S,S*)*–**(451)** but was initially isolated as a mixture with the *meso* isomer (*S,R*)*–**(451)** in a combined yield of 90.6%. Several features of the parent structures in both scenarios are highlighted and are noteworthy. These are; the reactivity of the cation is enhanced and isolation feasible as a result of charge delocalisation over the metal cluster. In terms of the stereoselectivity of the dimerisation step this is promoted as a consequence of the slipped stack chromophore–chromophore interaction and the 'bulky' metal centres which gives rise to limited conformational flexibility of the radical *via* space constraints near the site of the bond formation. [176]

An important comparison can be made with the literature example this is the reaction generated a novel product in high relative stereochemistry. Moreover, the literature emphasises the aromatic ring needs to be substituted in order for initial coordination *i.e.* the slipped stack arrangement of {CH, (OMe)/π–coordination, (Ar)} in order to get a good relative orientation and separation distance (R_{12}) of the two chromophore pairs. However, (*S,S*)*–**(446)** demonstrates that there is sufficient van der Waals forces between the surfaces of the flat aromatics to achieve the same effect.
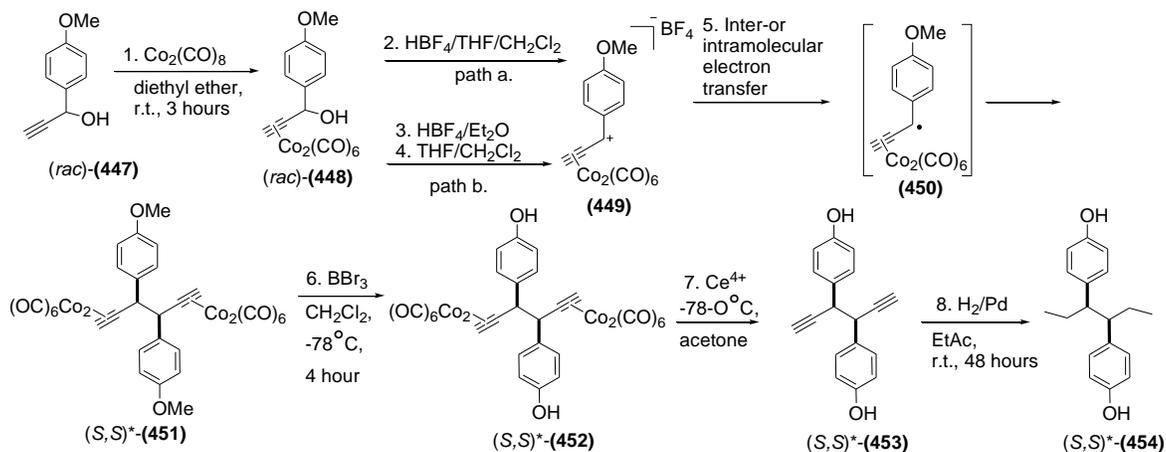
Scheme 101. Cobalt–templated radical coupling reactions. [176]

2.4   Conclusions.

During the process of investigating diyne synthesis, an dynamic kinetic resolution (DKR) was detected. It was reasoned from this observation that it may be possible to exploit this dynamic behaviour and thus several compounds were obtained in reasonably good diastereomeric ratios depending on reaction conditions. With respect to future work, this reaction can be used as a platform for the synthesis of heteroatom linked bicyclic aromatic derivatives *via* a metal catalysed [2+2+2] trimerisation reaction. Although these DKR reactions were initially very temperamental, this research has created an opportunity to readily generate an intermediate **(425)**, if the carbocationic centre of this intermediate can be stabilised it can be exploited for recognition chemistry *e.g.* future work may consider the synthesis of chiral triynes which could potentially control the relative 3,5,7–stereocenters **(460)** and make molecules like **(461)** and **(462)**,[177] or utilise the existing work on the Pauson Khand reaction and the recent advancements in this area by for example S. L. Buchwald [177] in asymmetric synthesis **(Scheme 102)**.
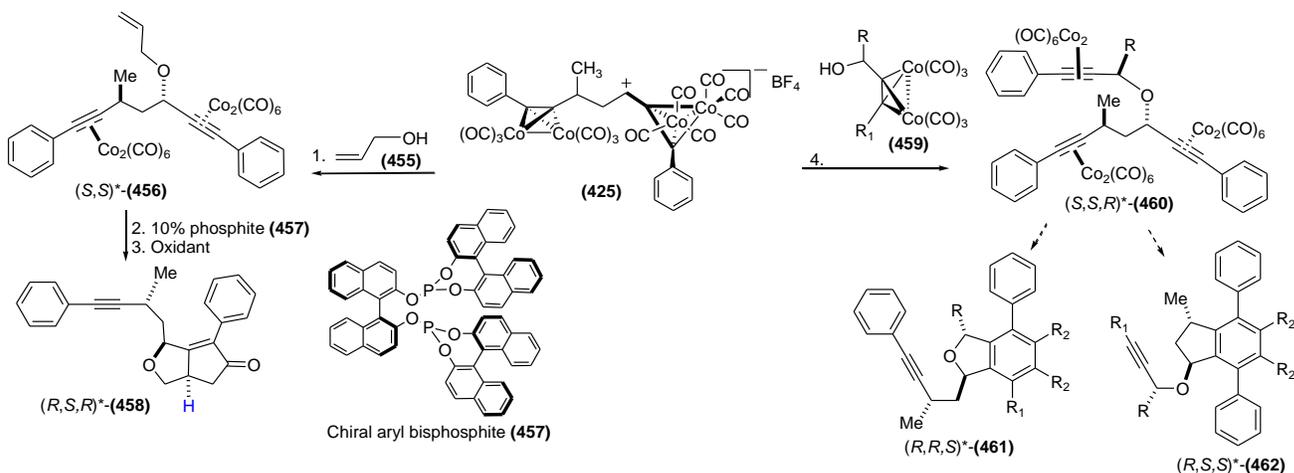
Scheme 102. Potential synthesis of two or three relatively defined stereogenic centres.

With respect to the one–pot synthesis of **(347)** the detection of diastereoselectivity suggests an alternative mechanism that would not go *via* a metallocyclopentadiene intermediate. This initially involves the generation of the Pauson Khand product **(467)** followed by the transition metal approaching from above or below the plane of cobalt complexed **(467)** in a intramolecular diastereoselective complexation in favour of (*S*,ₚ*S*)*. This is because the central element of chirality is

facing away relative to the approach of the transition metal. The poor diastereoselectivity could be because the central element of chirality is further away from the cyclopentadienone. Therefore, exerts less influence on the diastereomeric ratio of the planar chiral metallocene which would be in favour of (S,$_p$$S$)*–**(347)**. Thus, it could be concluded that this method has limitations they are carbon monoxide insertion cannot be avoided as it is an integral part of the mechanism if cyclobutadiene metallocenes are intended to be synthesised and the yield and diastereoselectivity is poor **(Scheme 103)**.
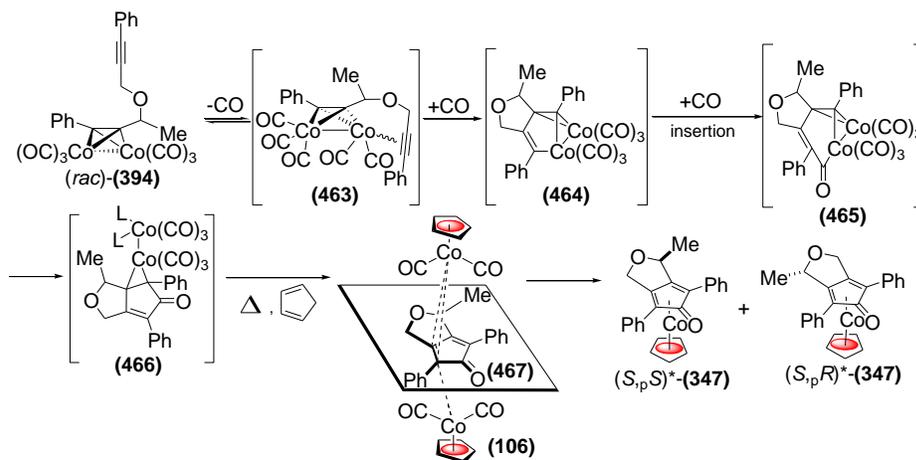
Scheme 103. Proposed mechanism for the synthesis of **(347)**.

Chapter Three

COBALT MEDIATED SYNTHESIS OF CHIRAL–AT–COBALT COMPLEXES.

3.0   Introduction to Chapter.

This chapter is a continuation of the research that was described in chapter two which explored suitable stoiciometric reagents in order to develop a method for diastereoselective complexation to give planar chiral cobalt metallocenes. This chapter briefly describes the concept of chiral–at–metal complexes as it is relevant to the complexes synthesised and the application of η^4–cyclobutadiene complexes in asymmetric synthesis. The aim of this chapter is to put into perspective the results which were observed when (η^5–cyclopentadienyl)*bis*(triphenylphosphine)cobalt was used on a variety of chiral diynes which are bridged with either an ether heteroatom or lactone group.

For absolute clarity (disclaimer), the chiral–at–cobalt metallocyclopentadiene complex (S_C,R_{Co},P)*–**(552)** was the <u>only</u> compound discovered by the former postgraduate researcher Dr Caroline J. Taylor who was in Dr Christopher J. Richards research group (2002–2006) in 10% yield, and reported in her PhD thesis.

3.1   Introduction to Chiral–at–Metal Complexes.

Chiral transition metal organometallics are an important class of compounds, some of which are characteristically identified by either having a stereogenic metal centre or axis of symmetry. [178]–[183] The first non–racemic organometallic chiral–at–metal species was reported by H. Brunner in the early 1970s. [182], [183] Select examples of chiral–at–metal compounds are illustrated in **Figure 34 (468)**, [182], [183] **(469)**, [184], [185] **(470)**, [186], [187] **(471)**, [186], [187] and **(472)**. [190]
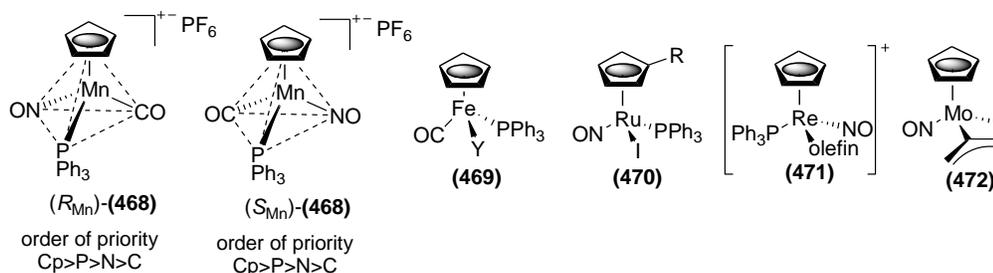
Figure 34. Examples of chiral–at–metal complexes. [182–190]

Many such examples of chiral–at–metal complexes exist to date. However, their application to asymmetric catalysis has been hindered in some cases because of the ease in which these complexes epimerise at the metal centre under catalytic reaction conditions which often require ambient temperatures. Moreover, epimerisation can also take place at –40°C. However, there have been some exceptions where the metal centred chirality is stable to racemisation when it is not subjected to harsh reaction conditions. With respect to diastereoisomers the relative stability can result in an enriched diastereoisomer as a consequence of unfavourable steric clashes in the other epimer. Moreover, epimerisation can take place directly after its formation thus this gives a diastereoisomer distribution proportional to the thermodynamic equilibrium **(Figure 35)**. [191]
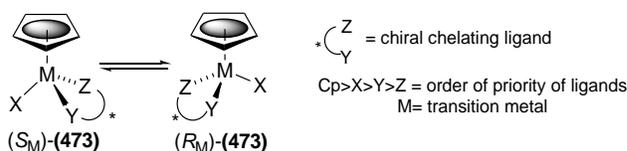
Figure 35. Epimerisation at the metal centre in enantiopure chiral chelating ligands. [191]

It was recently pointed out that the kinetic and thermodynamic stability of diastereoisomers is understood. [191] For example, after crystallisation a mixture of diastereoisomers is obtained and the wrong isomer is selected for X–ray crystallography then this would not reflect the true isomer distribution in the reaction. Thus X–ray crystallography alone is not enough to definitively assign the major diastereoisomer in a reaction. However, he also points out that the time scale is a significant factor as often diastereoisomers interconvert relatively quickly.

J. W. Faller, [191] proposes a guide when dealing with diastereoisomers which use transition metals as the chiral–at–metal source. This guide fervently warns to ensure a thermodynamic equilibrium is reached before confidently attributing a metal configuration. He states that for example low–spin d^6 transition metals *i.e.* Rh(III), Ir(III) and Ru(II) will undergo ligand dissociation or bond breaking at a rate which is significantly slower. There is the possibility of assigning a compound as a single diastereisomer when actually NMR data is that of two rapidly interconverting diastereoisomers.

H. Brunner highlights this misconception using complexes **(474) (Figure 36)** which resulted in H. D. Hansen & J. H. Nelson later conceding configurational lability at ruthenium [192] in their complexes, and by using the H. Brunner and T. Zwack [193] method they found that (η^6–cymene)RuX[C_6H_4CH(Me)NMe$_2$] (X= Cl or I) **(474)** existed as two diastereomers that are epimeric at ruthenium at room–temperature as determined by ^{1}H NMR spectroscopy. They revisited their own work looking at analogous complexes (η^6–C_6H_6)RuX[C_6H_4CH(Me)NMe$_2$] (X=N$_3$, NCO, NCS) and by dissolving crystals of these complexes in acetone–d^6 at –90°C, and obtaining ^{1}H NMR spectra of the resulting solutions at this temperature, they only observed resonances which were assigned to the major diastereomer of each complex. They learnt however that epimerisation took place at higher temperatures but produced the same equilibrium of the diastereomeric mixtures as they already reported.

(S_{Ru},R_C)-**(474)** major
η^6-C_6H_6>X>C_{Ar}>N

(R_{Ru},R_C)-**(474)** minor
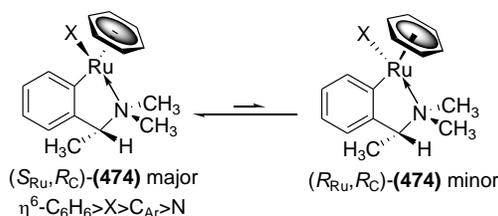
Figure 36. Configurational stability at ruthenium revisited. [198]

J. W. Faller, [193] offers a caveat with respect to the presence of a single diastereoisomer. Although there may possibly be some instances in which there are two diastereoisomers which are interconverting rapidly and the averaged NMR spectra suggests the presence of only one isomer, shifts in conformational equilibria present in a ligand *e.g.* a phosphine can give rise to epimers observed when considering the NMR spectrum. Therefore this would mean interconversion of chiral conformers as opposed to epimerisation at the metal. [194], [195]

As discussed by J. W. Faller, [193] different chemical shifts due to signals from different conformations of a ligand *e.g.* slow rotations of phenyl group about the P–C or P–M can be observed using high field NMR machines. This is because the averaging of the signal is dependent on the square of the chemical shift difference of the two different

conformations present in the ligand. Therefore by lowering the temperature of the NMR machine broadening can take place if rotation is taking place on a similar timescale. Similar effects may be seen at room temperature if the barrier of rotation is increased as a consequence of increased steric hindrance present in the ligand. Furthermore using different deuterated solvents maybe important as minor diastereoisomers can be more prominent due a change in the polarity of the solvent. [193]

J. W. Faller [193] also points out a major challenge for a chemist, which is if there are two isomers which have different configurations at metal or two diastereoisomers as a result of conformational present in the ligand, how do you definitively attribute the origin of isomerism? An investigation of this will be the general theme of this chapter. **Figure 37** illustrates the different conformations that can be present in a complex. Phenyl conformations (R_M,P)–**(475)** and (R_M,M)–**(475)** at phosphine is a possible element of chirality and has been investigated. [196] The analogue of propeller chirality is (R_M,P)–**(476)** and (R_M,M)–**(476)** which arises from diphenylphosphine examples of this behaviour have been reported to be present in P,P donor ligands like $(R,_pS)$–**(123)** 'Josiphos'. [63] Finally, polyhapto (η^6–arene) ring systems can give diastereomeric conformation *i.e.* $(R_{M,P}R)$–**(477)** and $(R_{M,p}S)$–**(477)** as a result of hindered rotation at *p*–cymene. [197], [198]
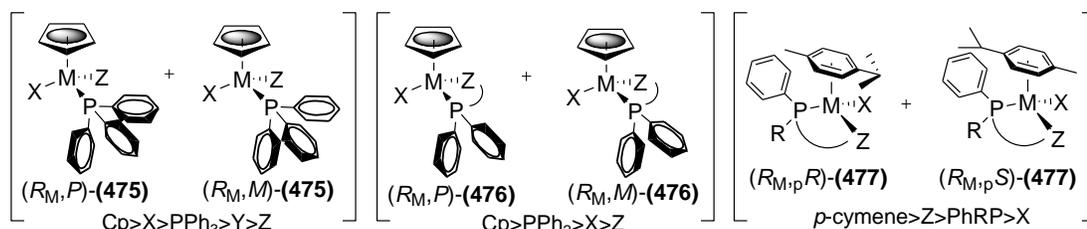
Figure 37. Examples of possible conformation in ligands.

Planar chiral cobalt metallocenes have been used as catalysts to convert trihaloacetimidates into allylic amines **(Scheme 104)**.[199] The diastereoselective metallation resulting in palladacycle $(S,_pS)$–**(478)** was highly dependent on the η^4–tetraphenylcyclobutadiene 'floor'. The bulky nature of the metallocene was found not only to dictate a diastereoselective metallation but to also aid in the context of promoting the approach of one prochiral face of the alkene during associative coordination. The aforementioned palladacycle catalyst after palladation becomes a dimer. Thus the true catalyst loading is 10 mol%, in order to achieve completion a 36 hour reaction time is necessary.
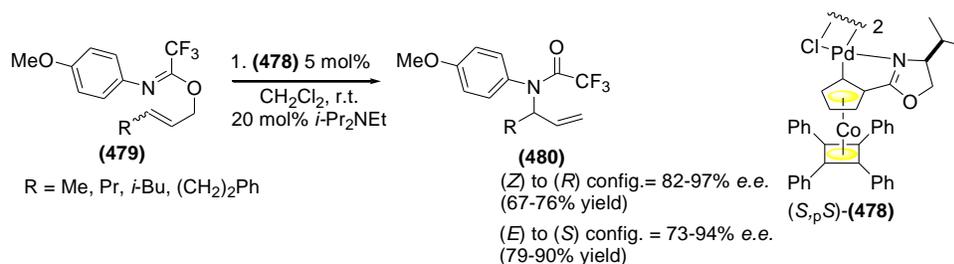
Scheme 104. Asymmetric rearrangement of *N*–aryl trifluoroacetimidates. [199]

The catalytic cycle in **Figure 38** shows mechanistically how the process of catalysis takes place.
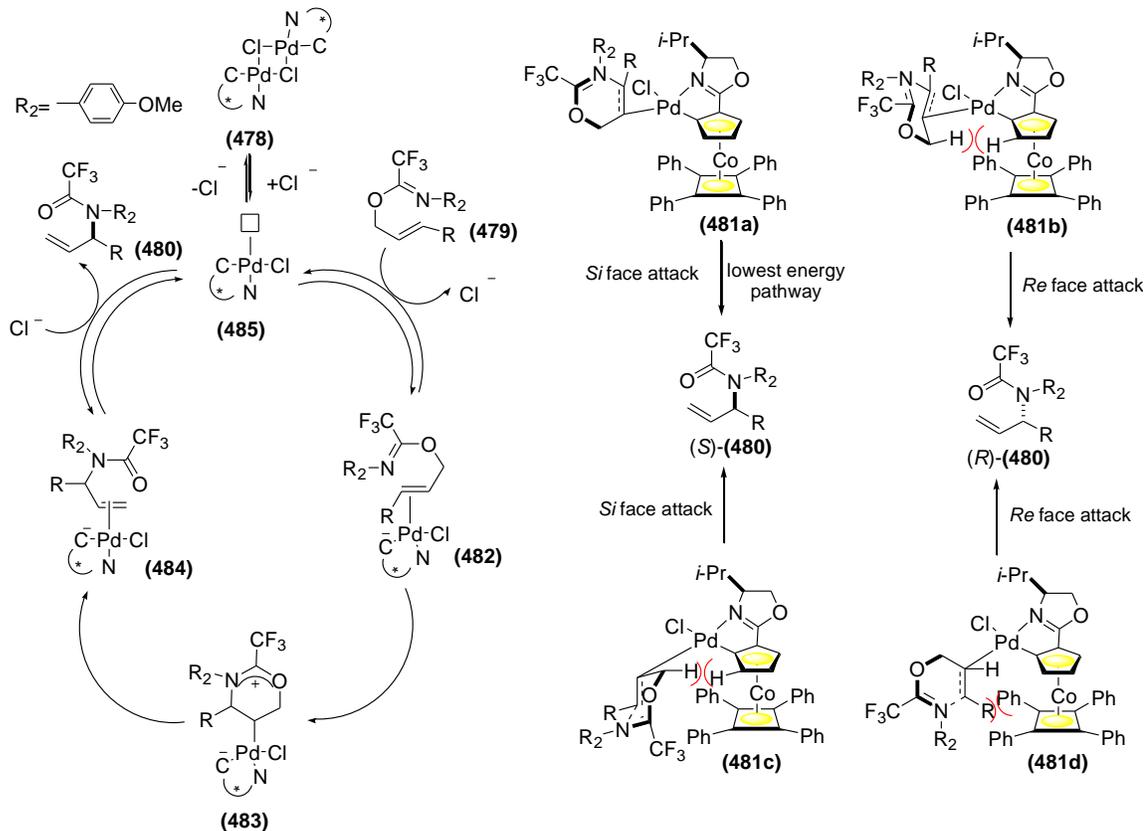
Figure 38. Cyclisation–induced rearrangement mechanism for COP–based catalysts. [199]

In 1977, H.Yamazaki & Y. Wakatsuki used (η^5–cyclopentadienyl)*bis*(triphenylphosphine)cobalt **(368)** to make a variety of (η^5–cyclopentadienyl)(triphenylphosphine)cobaltacyclopentadiene complexes by reacting a 2:1 ratio of starting material and reagent and stirring at room temperature for 1 hour. The position of the substituents in the end metallocycle was dependent on the arrangements of the two acetylenes in the *bis*acetylene intermediate and their dipole–dipole interactions. The carbon that forms a bond to cobalt in oxidative coupling was found to result in the formation of the more thermodynamically stable isomer. [200]

In a recent publication by C. J. Richards and co workers, the reaction of diarylacetylenes with CoCl(PPh$_3$)$_3$ **(100)** and sodium cyclopentadienylide or sodium carbomethoxycyclopentadienylide was investigated and reported to give (η^4–tetra–arylcyclobutadiene)(η^5–cyclopentadienyl)cobalt and (η^4–tetra–arylcyclobutadiene)(η^5–carbomethoxy cyclopentadienyl) cobalt, respectively, where aryl = *para*–XC$_6$H$_4$ (X = H,CF$_3$,F,MeO). All of the reactions produced, with one exception an intermediate (η^5–cyclopentadienyl)– or (η^5–carbomethoxycyclopentadienyl)(triphenylphosphine)–2,3,4,5–tetraarylcobaltacyclopentadiene complex was obtained. Heating the (η^5–cyclopentadienyl)– or (η^5–carbomethoxycyclopentadienyl)(triphenylphosphine)–2,3,4,5–tetraarylcobaltacyclopentadiene complexes resulted in clean conversion to the corresponding achiral metallocenes **(Scheme 105, Figure 39, Table 10** and **11)**. [201]
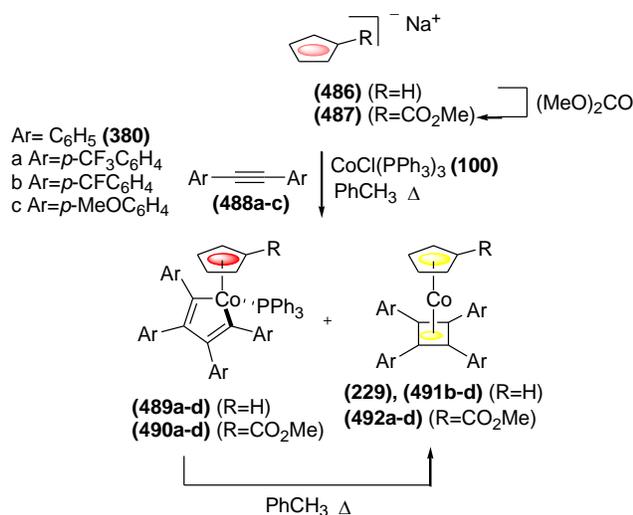
Scheme 105. General method for the synthesis of (η^4–tetra–arylcyclobutadiene)(η^5–cyclopentadienyl)cobalt and (η^5–cyclopentadienyl)(triphenylphosphine)–2,3,4,5–tetraarylcobaltacyclopentadiene and their derivatives. [201]
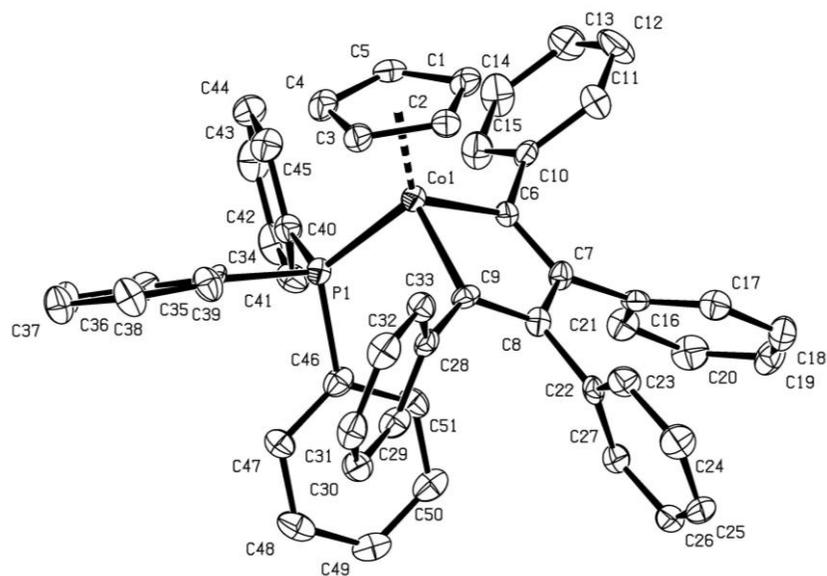

Figure 39. Molecular structure and atom numbering scheme for **(489a)** with 50% displacement ellipsoids, all H atoms are omitted for clarity. Selected bond distances (Å) and angles (°): C(9)–Co(1) 1.975(5), C(8)–C(9) 1.359(6), C(7)–C(8) 1.467(6), C(6)–C(7) 1.355(6), C(6)–Co(1) 1.987(4), Co(1)–P(1) 2.1914(13), C(9)–Co(1)–C(6) 82.49(19), C(9)–Co(1)–P(1) 94.56(14). [201]

Table 10. Synthesis of metallocyclopentadiene **(489)**, **(490)** complexes and η^4–cyclobutadiene metallocenes **(229)**, **(491)**, **(492)**. [201]

Entry	R	Ar	Reaction time (h)	Metallocyclopentadiene complex (yield)	η^4–Cyclobutadiene metallocene (yield)
1	H	Ph	5	**(489a)** (0%)	**(229)** (83%)
2	H	Ph	0.5	**(489a)** (90%)	**(229)** (0%)
3	H	p–$CF_3C_6H_4$	5	**(489b)** (54%)	**(491b)** (34%)
4	H	p–FC_6H_4	5	**(489c)** (6%)	**(491c)** (82%)
5	H	p–$MeOC_6H_4$	5	**(489d)** (0%)	**(491d)** (0%)
6	CO_2Me	Ph	15	**(490a)** (0%)	**(492a)** (73%)
7	CO_2Me	Ph	0.5	**(490a)** (10%)	**(492a)** (66%)
8	CO_2Me	p–$CF_3C_6H_4$	15	**(490b)** (88%)	**(492b)** (5%)
9	CO_2Me	p–FC_6H_4	15	**(490c)** (20%)	**(492c)** (47%)
10	CO_2Me	p–$MeOC_6H_4$	15	**(490d)** (0%)	**(492d)** (56%)

Table 11. Conversion of metallocyclopentadienyl complexes **(489)** and **(490)** into η^4–cyclobutadiene metallocenes **(229)**, **(491)** and **(492)**. [201]

Entry	Metallocyclopentadienyl Complex	Reaction time (h)	η^4–Cyclobutadiene metallocene (yield)
1	**(489a)**	5	**(229)** (95%)
2	**(489b)**	15	**(491b)** (81%)
3	**(489c)**	15	**(491c)** (92%)
4	**(490a)**	15	**(492a)** (82%)
5	**(490b)**	15	**(492b)** (96%)
6	**(490c)**	15	**(492c)** (97%)

The reaction mechanism with $CoCl(PPh_3)_3$ **(100)** as a stoiciometric source of Co(I) involves the initial formation of a (η^5–cyclopentadienyl)*bis*(triphenylphosphine) complex, followed by phosphine/alkyne substitution and oxidative cyclisation of the latter to give a Co(III) Lewis acidic intermediate. This is followed by either addition of triphenylphosphine to this coordinatively unsaturated intermediate resulting in **(489)** and **(490)** or reductive elimination to the η^4–cyclobutadiene complexes **(229)**, **(491)** and **(492)**. A slower rate of conversion where either Ar or the R functionality is an electron withdrawing group, is as a consequence of a slower rate of phosphine dissociation and increased Lewis acidity at the cobalt atom **(Figure 40)**. [201]
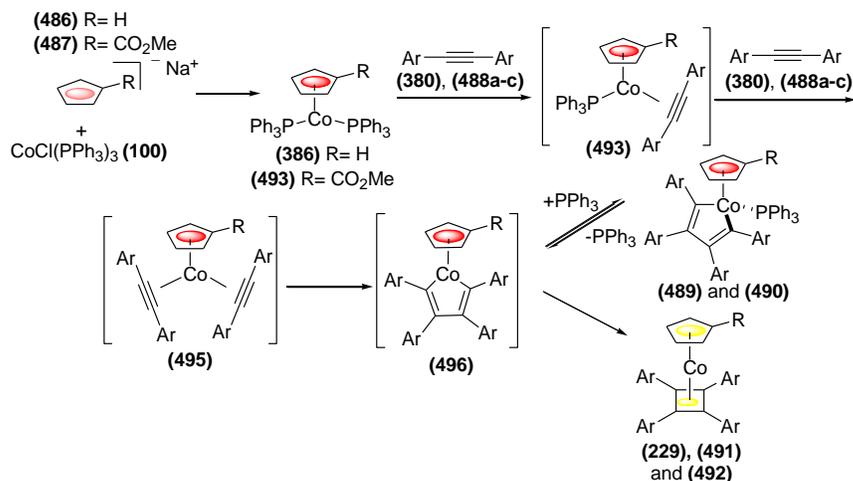
Figure 40. A reaction pathway accounting for the formation of metallocyclopentadiene complexes and η^4–cyclobutadiene metallocenes. [201]

It is noteworthy that the reaction of CoCl(PPh$_3$)$_3$ **(100)** with di(*para*–methyoxyphenyl)acetylene **(488c)** did not result in a metallocyclopentadiene complex bearing a coordinated triphenylphosphine ligand (**Table 10**, entry 10). Using dicarbonyl(η^5–cyclopentadienyl)cobalt **(106)** an insertion reaction took place to give a tetraarylcyclopentadienone metallocene **(381)** in 12% yield but not a corresponding η^4–cyclobutadiene complex. [201]

3.1   Objectives.

As stated in the introduction to this chapter an investigation into the effects of using different sources of cobalt(I) will be discussed. Preliminary screening of reagents suggested another good candidate for [2+2] cyclodimerisation would be CoCl(PPh$_3$)$_3$ **(100)** and sodium cyclopentadienide in the *in situ* generation of (η^5–cyclopentadienyl) cobalt(I)*bis*(triphenylphosphine) **(368)**. Chapter two revealed that dicobalt octacarbonyl can be used to make chiral diynes and although effective at synthesising planar chiral metallocyclopentadienones **(347)** it did not give any η^4– cyclobutadiene **(351)**. Therefore the new objectives were; develop a simple and high yielding route to synthesis of chiral ether and lactone bridged diynes. Explore the use of (η^5–cyclopentadienyl)cobalt(I)*bis*(triphenylphosphine) **(368)**.

Some objectives were made during the project that was as a consequence of the second objective. This was to create a library of chiral–at–metal ether and lactones complexes and investigate the origins of chirality present in two representative examples. This goal was anticipated to require the synthesis of enantiopure chiral–at–metal complexes.

3.2.   Results and Discussion.
3.2.1 Synthesis of Racemic Secondary Terminal Propargylic Alcohols.

Racemic secondary (terminal) propargylic alcohols (containing a single stereogenic centre) were synthesised in a two step procedure starting from commercially available phenylacetylene to give products in good yields (91–99%) **(Scheme 104)**. The *n*–butyl lithium used in this reaction was very important, high yields were observed when this reagent was stored properly. When phenylacetylene was deprotonated at low temperature using *n*–butyl lithium, a

colour change was readily apparent as the solution went from pale yellow to dark brown. The addition of the corresponding aldehyde allowed the anion created to be quenched resulting in another colour which was from dark brown and then to pale yellow. By giving the reaction mixture an aqueous work up the crude propargylic alcohols was extracted using ethyl acetate. The propargylic alcohols **(391)**, **(498)–(501)** were then purified under reduced pressure using kugelröhr or vacuum distillation equipment which removed dark impurities. Despite a second attempt to improve the yield for 4–(4–(trifluoromethyl)phenyl)but–3–yn–2–ol **(500)**, 91% was the highest yield obtained. Possibly because CF_3 is an electron withdrawing group which stabilises the resultant carbanion generated after treatment with *n*–butyl lithium, thus deactivating the full potential of this carbanion for nucleophilic attack.

Evidence to support the synthesis of the chiral propargyl alcohols discussed include **(Scheme 106)**; IR spectra showing an OH stretch at *ca.* 3200 cm^{-1}. The ^1H NMR spectrum showed *J* coupling of the *H*C with the R_1 functionality at *ca.* δ 4.7 ppm in **(391)** and **(498)**. Also, all the propargyl alcohols were known compounds, literature citation details of the molecules and their characterisation data were consistent.
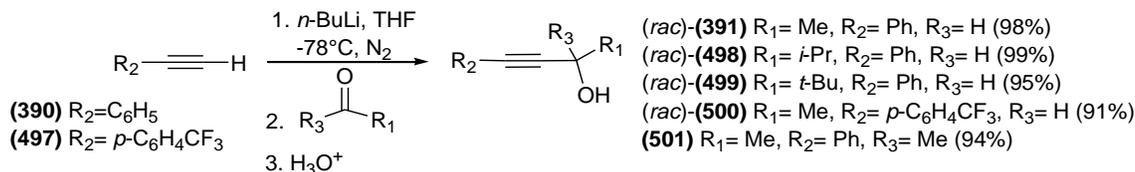
Scheme 106. General procedure for the preparation of propargyl alcohol.

3.2.2 Synthesis of Ether Diynes.

Propargyl alcohols **(391)**, **(397)** and **(498)** were used to make ether bridged diynes. Initially the Lewis base 18–crown–6 (0.5 equiv.) was used in conjunction with propargyl bromide and by heating to reflux in saturated aqueous potassium hydroxide was found to give moderately good yields (method 1a). However, a simpler method (method b) which used only NaH (60% dispersed in mineral oil) at a much lower temperature of only 60°C was found to be more effective **(Scheme 107)**, for example giving **(504)** in nearly quantitative yield. However it was experimentally established in repeated synthesis that heating at a higher temperature overnight could lead to formation of 1,3–dihydronaphtho[2,3–c]furan **(505)** as a by product in 61% yield.

Spectroscopic techniques were used to identify the chiral diynes. The IR spectrum showed absences of an OH stretch which is normally observed at *ca.* 3280–3295 cm^{-1}. The ^1H NMR spectra **(502)** and **(503)** showed the presence of two doublet of doublets at *ca.* δ 4.3 ppm assigned to the OCH_2 moiety, and a triplet at *ca.* δ 2.5 attributed to the terminal acetylene unit. The ^1H and ^{13}C NMR data and yield were found to agree with the literature reports. [161], [203]
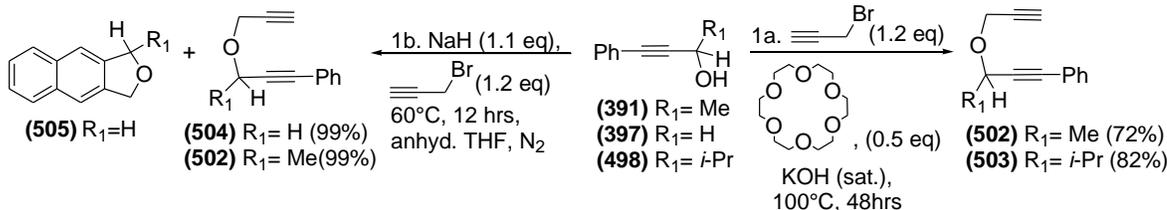
Scheme 107. General procedure for the synthesis of ether diynes.

3.2.3 Synthesis of Diynes using the Sonogashira Reaction.

The Sonogashira reaction[(204)] **(Figure 41)** was used to cross–couple ether diynes **(502)**, **(503)**, **(504)** with aryl halides giving ether bridged arylethynylenes **(Scheme 108, Table 12)** in good yields (94–99%). Using 3 mol% of PdCl$_2$(PPh$_3$)$_2$ with 10 mol% of the co–catalyst copper (I) iodide gave better yields compared to the use of 3 mol% of Pd(PPh$_3$)$_4$ with 10 mol% of CuI and heating to reflux for 24 hours **(Table 12)**. Using freshly distilled triethylamine and covering the reaction with aluminium foil to prevent sunlight exposure and conducting the reaction in an inert atmosphere prevented the formation of homocoupled acetylene products.

The palladium catalytic cycle begins with the generation of a 14 electron Pd(0)L$_2$ species *in situ* which reacts with the aryl halide by oxidative addition to give a Pd(II) complex. In a rate limiting step, transmetallation takes place forming a copper acetylide compound. The organic ligands undergo *trans–cis* isomerisation to give a *cis* orientated product. In a reductive elimination process the diyne is liberated which results in regeneration of the Pd(0) catalyst **(Figure 41)**.
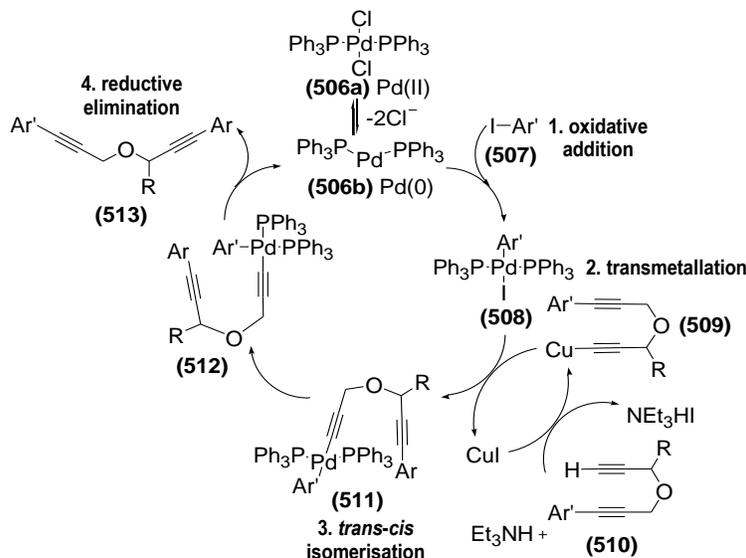
Figure 41. General mechanism for Sonogashira cross coupling.

To support the diyne identity a comparison was made between the ether diyne systems and the cross coupled products. It was evident that for example using **(502)** as a representative example to which **(343)** gave an AB system for OCHH[1] and showed two mutually coupled doublets with a coupling constant of *J* 15.7 Hz at δ 4.32 and δ 4.35 ppm each of which shows a coupling of *J* 2.5 Hz to the alkyne proton at δ 2.45 ppm was no longer present. But instead two mutually coupled doublets at δ 4.51 and δ 4.66 ppm with a *J* 15.6 Hz coupling constant for each diastereotopic OCHH[1]

proton. With respect to **(503)** R_1= *i*–Pr the methylene group gave a doublet which was observed to couple acetylene proton which was a triplet (*J* 2.5 Hz). However, after cross coupling the methylene group appears as two mutually coupled doublets with a coupling constant of *J* 16.0 Hz. Additional ^{19}F NMR spectrums were collected for **(522)** and **(523)** which indicated coupling to ^{1}H and [13]C. For example, the ^{13}C NMR spectrum of **(523)** gave a quartet with [1]*J* 16.0 Hz coupling for CF_3 at δ 130.4 ppm. The ^{13}C NMR for **(522)** gave a doublet with a coupling constant of [1]*J* 4.0 Hz at δ 118.8 ppm both consistent with short range coupling in the aromatic region. The ^{1}H and ^{13}C NMR spectrum of **(343)** and **(344)** agreed with the literature values. [161]
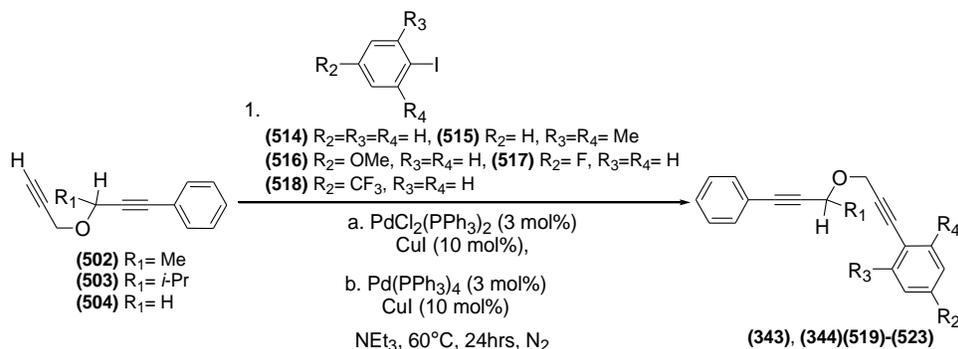
Scheme 108. General procedure for the Sonogashira reaction of ethers diynes.

Table 12. Functionalisation of ether bridged diynes by Sonogashira coupling.

Starting material	Compound	Entry	R_1	R_2	R_3	R_4	Method A Yield (%)	Method B Yield (%)
(504)	**(519)**	1	H	H	H	H	Quant.	–
(504)	**(520)**	2	H	H	Me	Me	Quant.	–
(504)	**(521)**	3	H	OCH_3	H	H	(99%)	–
(504)	**(522)**	4	H	F	H	H	(94%)	–
(502)	**(523)**[202]	5	Me	CF_3	H	H	(96%)	–
(502)	**(343)**[161]	6	Me	H	H	H	(97%)	(69%)
(503)	**(344)**[161]	7	*i*–Pr	H	H	H	(95%)	(76%)

3.2.4 Synthesis of Iodo Ester Bridged Systems.

Using the chiral propargyl alcohols **(391)**, **(397)**, **(426)**, **(498)**–**(501)**, iodo ester derivatives were prepared in 91–99% yield using the Steglich esterification [205] procedure **(Scheme 109, Table 13)**. This method was chosen because the reaction conditions were mild and it is known to work well with sterically demanding reagents. The crude mixture was given an aqueous work up using 1 M HCl which removed unreacted 4–*N,N*–dimethylaminopyridine (DMAP) followed by column chromatography with either a 9:1 or 7:3 hexane/ethyl acetate mixture of solvents. A catalytic amount of DMAP (5 mol%) was employed as an acyl transfer reagent as it accelerates the rate of reaction because it is a stronger nucleophile than the propargylic alcohol. Moreover, it reacts with the intermediate *o*–acylisourea to give a reactive amide helping to prevent the formation of intramolecular side products.
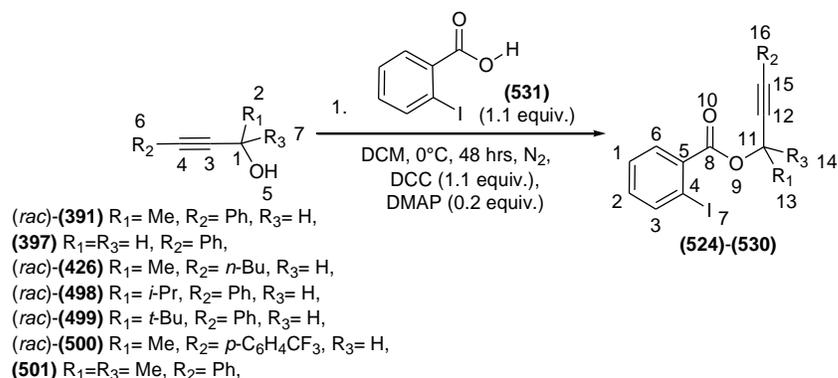
Scheme 109. General procedure for the preparation of esters.

Table 13. Selected ester derivatives.

Starting compound	Product	Entry	R_1	R_2	R_3	Yield (%) (1a)	Yield (%) (1b)
(397)	(524)	1	H	Ph	H	99%	–
(391)	(525) [161]	2	Me	Ph	H	99%	45%
(500)	(526)	3	Me	p–$CF_3C_6H_4$	H	91%	–
(498)	(527) [161]	4	i–Pr	Ph	H	95%	68%
(499)	(528) [202]	5	t–Bu	Ph	H	95%	–
(426)	(529)	6	Me	n–Bu	H	98%	–
(501)	(530)	7	Me	Ph	Me	95%	–

The other known methodology for the synthesis of iodo esters involved heating 2–iodobenzoic acid **(531)** to reflux in thionyl chloride for 12 hours creating the acid chloride **(532)** *in situ,* removing excess thionyl chloride *in vacuo,* and the adding the propargylic alcohol. This methodology gave yields for **(525)** and **(527)** of 45% and 68% respectively slightly lower than those found previously of 57% and 70% yield. [202]

The presence of a carbonyl stretch at *ca.* 1700 cm⁻¹ for each iodo ester compound supported esterification. ¹³C NMR spectra all showed a relatively intense carbonyl peak at *ca.* δ 165.0 ppm suggesting an ester linkage. Moreover, both ¹H and ¹³C NMR data indicated a downfield shift as a result of deshielding for R_1, R_3 at C11 **(Scheme 109)**. For example, the ¹H NMR spectrum of *rac*–**(391)** shows signals at δ 1.54 ppm (3H, d, *J* 6.6 Hz, 1–C*H₃*) and δ 4.76 (1H, q, *J* 6.6 Hz, 1–C*H*) and after esterification **(525)** showed δ 1.72 (3 H, d, *J* 6.7 Hz, 11–C*H₃*), δ 5.93 (1 H, q, *J* 6.7 Hz, 11–C*H*). Another characteristic feature of this type of esterification was the emergence of 3 peaks in the ¹³C NMR spectra between δ 80–100 ppm corresponding to C5, C12 and C15. Compounds **(525)**, **(527)** and **(528)** have been previously synthesised and the spectroscopic data for these were as previously reported. [161], [202]

(524) and **(530)** both of which do not have a stereogenic centre were synthesised in order that they could be made in to ester diynes and used as a controlled experiment. This was thought to provide information about the influence the molecules have when they are achiral and used to make planar chiral metallocenes or their precursor complexes. To

support the identity of **(524)** the ^{1}H NMR spectrum gave a singlet peak at δ 5.03 ppm which integrated for two protons this was correlated to the signal in the ^{13}C NMR spectrum at δ 53.9 ppm (*CH$_2$*). Correlation studies helped to support the structure of **(530)** at δ 1.91 ppm a singlet that integrated for six protons was correlated to a signal in the ^{13}C NMR spectrum at δ 29.4 ppm (2x*CH$_3$*). High resolution mass spectrometry was consistent with the molecular weight expected. The IR spectrum showed a strong carbonyl stretch at 1718 cm^{-1} for **(524)** and 1731 cm^{-1} for **(530)**.

(526) where R$_2$= *p*–CF$_3$C$_6$H$_4$ gave a doublet signal at δ 1.67 ppm and a quartet at δ 5.48 ppm with a coupling constant of ^3J 6.7 Hz. The ^{13}C NMR spectrum gave a quartet signal at δ 130.2 ppm which had a coupling constant of ^1J 33.0 Hz which was δ +4.3 ppm higher than the propargyl alcohol **(500)**.

3.2.5 Synthesis of Ester linked diynes using the Sonogashira reaction.

Using the iodo esters **(524)**–**(530)**, Sonogashira cross coupling gave ester diynes **(345)**, **(346)**, **(533)**–**(543)**, **(548)**, **(549)** in yields >93%. To investigate the effect of different functionalities on diastereoselective complexation a library of chiral diynes was created (**Scheme 110, Table 14** and **Scheme 111**).
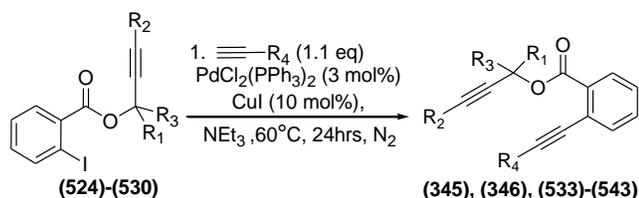
Scheme 110. Synthesis of ester linked diynes.
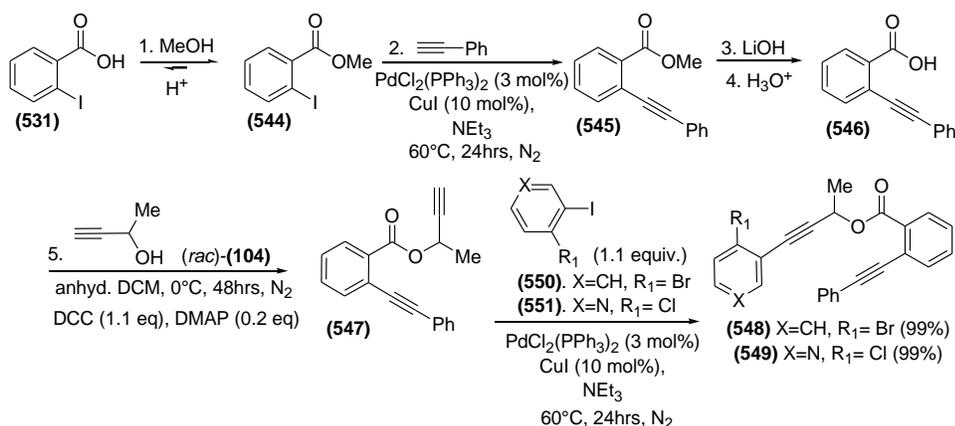
Scheme 111. An alternative procedure for the synthesis of diynes **(548)** and **(549)**.

Table 14. Diynes synthesised using the Sonogashira cross coupling reaction.

Starting compound	Product	Entry	R_1	R_2	R_3	R_4	Yield (%)
(524)	(533)	1	H	Ph	H	Ph	(98%)
(524)	(534)	2	H	Ph	H	p–CF$_3$C$_6$H$_4$	(94%)
(525)	(345)	3	Me	Ph	H	Ph	(99%)
(526)	(535)	4	Me	p–CF$_3$C$_6$H$_4$	H	Ph	(96%)
(525)	(536)	5	Me	Ph	H	p–CF$_3$C$_6$H$_4$	(93%)
(526)	(537)	6	Me	p–CF$_3$C$_6$H$_4$	H	p–CF$_3$C$_6$H$_4$	(94%)
(527)	(346)	7	i–Pr	Ph	H	Ph	Quant.
(528)	(538)	8	t–Bu	Ph	H	Ph	(99%)
(529	(539)	9	Me	n–Bu	H	Ph	(97%)
(530)	(540)	10	Me	Ph	Me	Ph	(96%)
(525)	(541)	11	Me	Ph	H	SiMe$_3$	(92%)
(525)	(542)	12	Me	Ph	H	3–NC$_5$H$_4$	(98%)
(525)	(543)	13	Me	Ph	H	o–OCH$_3$C$_6$H$_4$	(95%)

To support the synthesis of cross–coupled ester diyne in **Scheme 110, Table 14** and **Scheme 111**. The ^{13}C NMR spectrum for each diyne was inspected for the absence of a peak attributed to the carbon attached to iodine which was known to appear at *ca.* δ 95.0 ppm. Moreover, an additional two peaks which are assigned to the new acetylene moiety are found at *ca.* δ 80–100 ppm as well as more peaks in the aromatic region. Diynes **(345)** and **(346)** are known compounds and their data agree with that reported previously. [161], [202] Where data could not be corroborated the compounds were fully characterised. An alternative procedure was developed and used to make diynes **(548)** and **(549)** both in yields of 99% for the final step **(Scheme 111)**. Both new compounds were fully characterised. A characteristic feature of the diyne **(548)** was a stretch at 550 cm^{-1} for a C–Br. The emergence of new peaks in the aromatic region of the ^{1}H and ^{13}C NMR spectra and an absence of a 14*C*H peak at *ca.* δ 67.0 ppm attributed to the acetylene unit was additional evidence. High resolution mass spectroscopy gave molecular ions of each isotope of **(548)** corresponding to [M]$^+$= C$_{25}$H$_{17}$^{79}BrO$_2$ and C$_{25}$H$_{17}$^{81}BrO$_2$ using electron impact ionisation and **(549)** [M+H]$^+$= C$_{24}$H$_{17}$^{35}ClNO and C$_{24}$H$_{17}$^{37}ClNO using electrospray ionisation.

3.2.6 Synthesis of 7,5–membered Cyclic Lactone Complexes.

The first report and full characterisation of the 7,5–membered cyclic lactone complex (S_C,R_{Co},P)*–**(552)** was made by C. J. Taylor **(Scheme 112)**. Using (*rac*)–diyne **(345)**, which has only one stereogenic centre, treatment with a stoiciometric amount of CoCl(PPh$_3$)$_3$ **(100)** and Na(C$_5$H$_5$) **(486)** in anhydrous toluene and heating to reflux for 18 hours in a concerted [2+2] oxidative cyclisation process gave this novel lactone complex (S_C,R_{Co},P)*–**(552)** albeit in only 10% yield. The relative stereochemistry of this complex was deterermined using X–ray crystallography by Majid Metovelli for the compound synthesised by C. J. Taylor. [202]
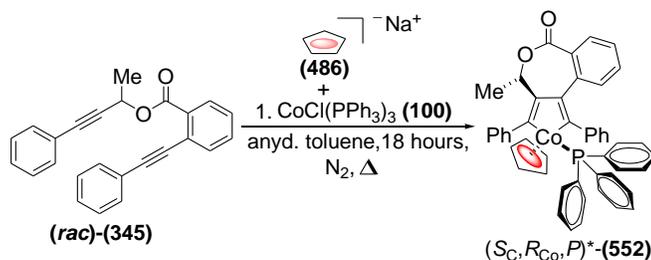
Scheme 112. Synthesis of (S_C,R_{Co},P)*–**(552)**. [202]

C. J. Taylor found that heating (S_C,R_{Co},P)*–**(552)** to high temperature did not lead to η^4–cyclobutadienecobalt complex **(353)**. [202] The reaction illustrated in **Scheme 112** was carefully repeated using racemic diyne **(345)**. ^{1}H NMR spectrum of the crude product showed broad peaks at *ca.* δ 4–5 ppm indicating η^5–cyclopentadienyl type species, but not at δ 4.83 ppm (5H, s, C_5H_5) corresponding to the η^5–Cp of (S_C,R_{Co},P)*–**(552)**. Triphenylphosphine appeared to be a major contaminate amongst others in the reaction. Purification was attempted but was unsuccessful.

It was reasoned that perhaps the reaction conditions should be changed. Using the reaction conditions developed to make cobaltocycle **(489a)** (**Table 10**, entry 2 which gave a 90% yield), a shorter reaction time of only 0.5 hours and a lower temperature of 60°C in anhydrous tetrahydrofuran was used with 1 equivalent of *rac*–**(345)**, 1.4 equiv. of CoCl(PPh$_3$)$_3$ **(100)** and 1.4 equiv. of Na(C$_5$H$_5$) **(486)**. This set of conditions worked well as it gave (S_C,R_{Co},P)*–**(552)** in 45% yield. Moreover, the yield was improved to 75% using (Co(PPh$_3$)$_2$(η^5–C$_5$H$_5$) **(368)** and *rac*–**(345)** in a 1:1 ratio. Both methods required an aqueous work up followed by purification using column chromatography (3:7 or 1:19 ethyl acetate/ hexane) **(Scheme 113)**.
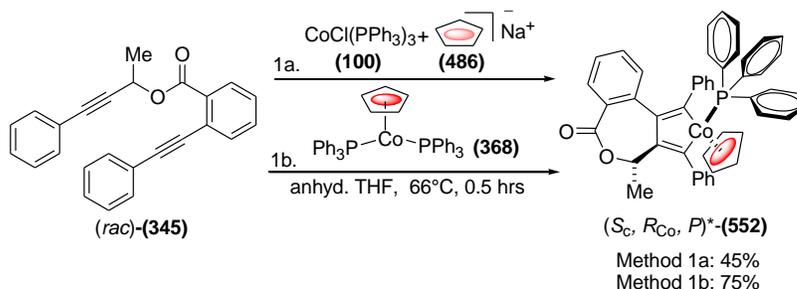
Scheme 113. Method developed for the synthesis of (S_C,R_{Co},P)*–**(552)**.

The ^{1}H and ^{13}C NMR were consistent with those reported previously. Using the two methods (1a, b), extensions were made to other examples using ester diynes **(346)**, **(524)**, **(533)**–**(535)**, **(537)**–**(543)**, **(547)**–**(549)** illustrated in **Scheme 114**, **Table 15** and **16**.
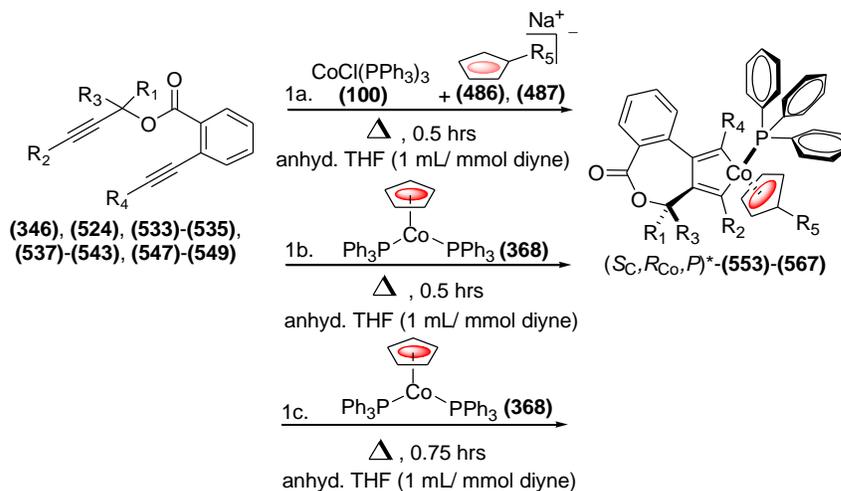
Scheme 114. Diastereoselective synthesis of chiral lactone complexes.

Better yields were obtained with only 1 equivalent of (η^5–cyclopentadienyl)*bis*(triphenylphosphine)cobalt(I) **(368)** (entries 4,6,14 and 15 of **Table 15)**. The reaction worked well with the notable exception of (S_C,R_{Co},P)*–**(554)** which was not formed despite varying the reaction conditions employed. Reaction conditions 1c. gave a 90% isolated yield for (S_C,R_{Co},P)*–**(558)** however gave no improvement when applied to the synthesis of (S_C,R_{Co},P)*–**(552)** from **(345)**. Diyne **(547)** did not form a metallocyclopentadiene complex. This was thought to be as a result of the presence of the terminal alkyne. A similar result was also observed for the attempted synthesis of **(562)** R_2=SiMe$_3$ which gave a 16% yield of **(547)** R_2=H through cleavage of the silyl group. Diyne **(539)** (R_2= *n*–Bu) gave (S_C,R_{Co},P)*–**(560)** in a modest yield of 60% compared to other groups containing electron withdrawing substituents, *e.g. p*–CF$_3$C$_6$H$_4$ which gave yields that are >70% under the same reaction conditions.

When (η^5–C$_5$H$_5$)(PPh$_3$)$_2$Co **(368)** was used on the chiral diyne **(525)** where R_2=C$_6$H$_4$OMe diastereoselective complexation gave metallocyclopentadiene complex (S_C,R_{Co},P)*–**(564)** with a yield of 74%. This example shows at least one electron donating group can be used to synthesise complexes of this type. This result is in contrast to the unsuccessful attempted synthesis of **(489d)** where the aryl groups are *para*–methoxyphenyl (**Scheme 105, Table 10,** and entry 10)**.**

Table 15. Results for 7,5–membered cyclic lactone complexes.

Diyne	Complex	Entry	R₁	R₂	R₃	R₄	R₅	Yield (%)[a]		
(533)	**(553)**	1	H	Ph	H	Ph	H	1a: 40%		
(534)	**(554)**	2	H	Ph	H	p–CF₃C₆H₄	H	–		
(535)	**(555)**	3	Me	p–CF₃C₆H₄	H	Ph	H	1a: 76%		
(536)	**(556)**	4	Me	Ph	H	p–CF₃C₆H₄	H	1a: 75%	1b: 81%	
(537)	**(557)**	5	Me	p–CF₃C₆H₄	H	p–CF₃C₆H₄	H	1a: 65%		
(346)	**(558)**	6	i–Pr	Ph	H	Ph	H	1a: 55%	1b: 80%	1c: 90%
(538)	**(559)**	7	t–Bu	Ph	H	Ph	H	1a: 43%		
(539)	**(560)**	8	Me	n–Bu	H	Ph	H	1a: 60%		
(540)	**(561)**	9	Me	H	Me	Ph	H	–		
(541)	**(562)**	10	Me	Ph	H	SiMe₃	H	–		
(542)	**(563)**	11	Me	Ph	H	3–NC₅H₄	H	1b: 90%		
(543	**(564)**	12	Me	Ph	H	o–OCH₃C₆H₄	H	1b: 74%		
(547)	**(565)**	13	Me	H	H	Ph	H	–		
(548)	**(566)**	14	Me	o–Br C₆H₄	H	Ph	H	1a: 73%	1b: 86%	
(549)	**(567)**	15	Me	2–Cl–4–pyridyl	H	Ph	H	1a: 54%	1b: 80%	

[a]. Isolated yield after silica gel column chromatography.

Ester diynes **(345)**, **(346)**, **(524)**, **(535)**, **(538)** and **(539)** were used to investigate the influence of the Cp substituent (R₅= CO₂Me) on the yield. The results in **Table 16** show there is no constituent effect.

Table 16. Results for 7,5–membered cyclic lactone complexes (carbomethoxy cyclopentadienyl).

Diyne	Complex	Entry	R₁	R₂	R₃	R₄	R₅	Yield (%)[a]
(345)	**(568)**	1	Me	Ph	H	Ph	CO₂Me	1a: 63%
(346)	**(569)**	2	i–Pr	Ph	H	Ph	CO₂Me	1a: 61%
(538)	**(570)**	3	t–Bu	Ph	H	Ph	CO₂Me	1a: 51%
(536)	**(571)**	4	Me	Ph	H	p–CF₃C₆H₄	CO₂Me	1a: 68%
(535)	**(572)**	5	Me	p–CF₃C₆H₄	H	Ph	CO₂Me	1a: 51%
(539)	**(573)**	6	Me	n–Bu	H	Ph	CO₂Me	1a: 65%

[a]. Isolated yield after silica gel column chromatography.

To confirm the identity of the chiral–at–metal lactone complexes X–ray crystal structures were obtained. **Figure 42, 43** shows the X–ray crystal structure of (S_C,R_{Co},P)*–**(555)** and (R_C,S_{Co},M)*–**(566)** which illustrate the relative stereochemistry of the central, chiral–at–metal, and propeller elements of chirality. **Table 17** and **18** presents a spectroscopic comparison of the major cobaltacyclopentadiene isomer synthesised in **Table 15** and **Table 16**.
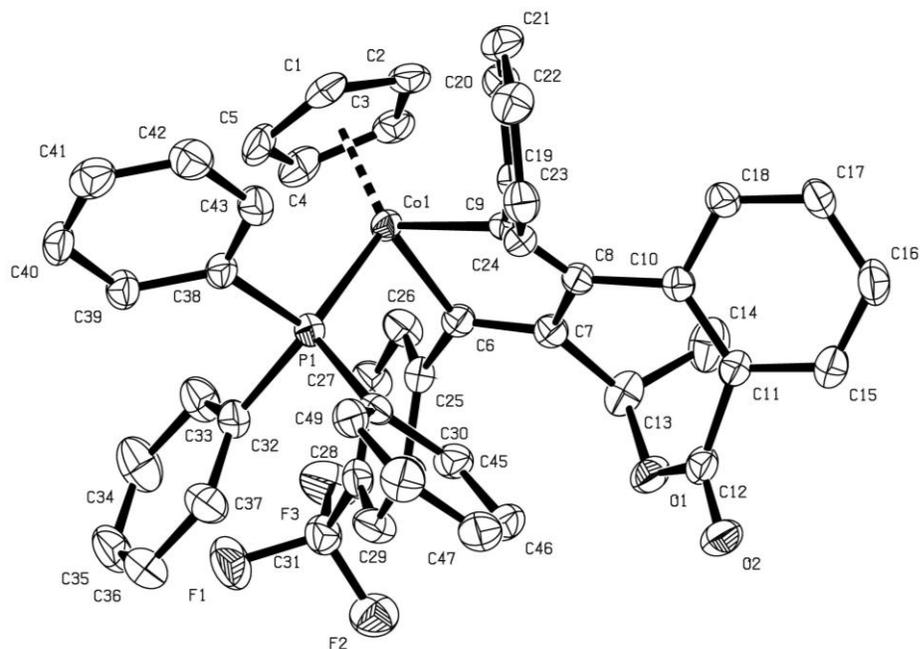
Figure 42. Molecular structure and atom numbering scheme for $(S_C, R_{Co}, P)^*$–**(555)** with 50% displacement ellipsoids, all H atoms are omitted for clarity. Selected bond distances (Å) and angles (°): C(6)–Co(1) 1.987(4), C(6)–C(7) 1.355(6), C(7)–C(8) 1.467(6), C(8)–C(9) 1.359(6), C(9)–Co(1) 1.975(5), Co(1)–P(1) 2.1914(13), C(13)–C(14) 1.3900, C(9)–Co(1)–C(6) 82.49(19), C(9)–Co(1)–P(1) 94.56(14).
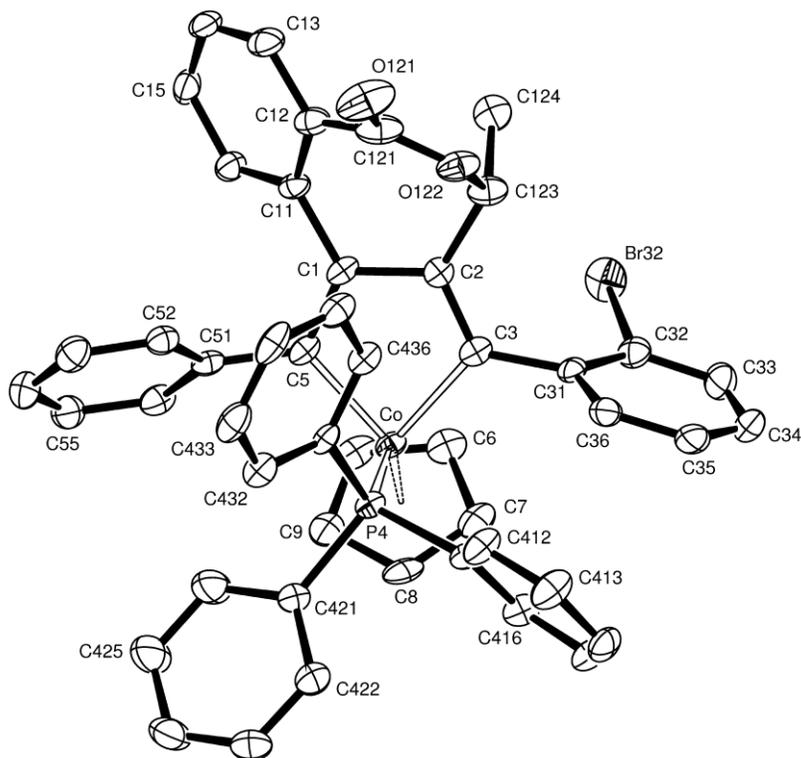
Figure 43. Molecular structure and atom numbering scheme for $(R_C, S_{Co}, M)^*$–**(566)** with 50% displacement ellipsoids, all H atoms are omitted for clarity. Selected bond distances (Å) and angles (°): C(2)–C(3) 1.341(3), C(1)–C(2) 1.465(3), C(1)–C(5) 1.359(3), Co–C(5) 1.976(2), Co–C(3) 1.981(3), Co–P(4) 2.2080(7), C(5)–Co–P(4) 93.95(7), C(121)–O(122)–C(123) 122.1(2).

Table 17. Spectroscopic characterisation of the major cobaltacyclopentadiene isomer.

Entry	Complex	IR (cm^{-1})	NMR (δ ppm) in CDCl$_3$			M.P.
		C=O	δ^{1}H (C$_5$H$_5$)	δ^{13}C (C$_5$H$_5$)	δ^{31}P (PPh$_3$)	
1	**(552)**	1689	4.83	89.6	49.3	208–210°C
2	**(553)**	1699	4.86	89.4	54.3	150–152°C
3	**(555)**	1693	4.82	89.6	48.6	198–200°C
4	**(556)**	1733	4.80	89.7	48.5	178–180°C
5	**(557)**	1693	4.84	89.6	48.0	150–152°C
6	**(558)**	1734	4.81	89.7	49.6	208–210°C
7	**(559)**	1780	4.81	90.1	49.6	210–212°C
8	**(560)**	1734	4.89	87.5	52.3	161–163°C
9	**(563)**	1700	4.80–4.90	89.9	49.4	206–208°C
10	**(564)**	1693	4.71	88.5	49.5	150–152°C
11	**(566)**	1734	4.97	88.8	47.1	148–150°C
12	**(567)**	1695	4.96	88.1	47.3	198–200°C

Table 18. Spectroscopic characterisation of the major cobaltacyclopentadiene (CO$_2$Me) isomer.

Entry	Complex	IR (cm^{-1})	NMR (δ ppm) in CDCl$_3$			M.P.
		C=O	δ^{1}H (CO$_2$CH$_3$)	δ^{1}H (R$_3$= CH)	δ^{31}P (PPh$_3$)	
1	**(568)**	1694	3.57	4.96	50.0	178–180°C
2	**(569)**	1733	4.04	4.78	52.1	–
3	**(570)**	1717	3.71	4.36	50.0	160–162°C
4	**(571)**	1695	3.59	4.95	49.2	170–172°C
5	**(572)**	1701	3.62	4.95	49.8	168–170°C
6	**(573)**	1717	3.62	5.48	51.2	160–162°C

Predominantly a single diastereoisomer was observed by ^{1}H NMR spectroscopy, together with three minor sets of signals, for all the lactone complexes synthesised **(Table 19)**. In the parent reaction which gave (S_C,R_{Co},P)*–**(552)**, this ratio corresponded to *ca. d.r.*= 11:1:1:1. After recrystallisation and examination of this material the same ratio of signals was present. This was the case even when the ^{1}H NMR spectrum was recorded within minutes of dissolving the crystals at room temperature (20.7°C). Variable temperature (V.T.) experiments at –20, 20, 40 and 60°C showed no major change in the isomer distribution. This rapid isomer distribution suggested that it did not involve epimerisation of the metal centered element of chirality since this involves phosphine dissociation. When 1.5 equiv. of *tris*(*para*–tolyl)phosphine was added to 1 equiv. of (S_C,R_{Co},P)*–**(552)** in 1 mL of CDCl$_3$, and spectrum recorded in 1 hour intervals, the ^{1}H NMR spectrum remained unchanged and no new species was detected.

Thus isomers may arise from possibly a) propeller chirality, and b) the conformational flexibility of the seven membered lactone ring. Moreover, it was also thought these were linked *i.e.* flexibility of the seven membered ring is correlated to phosphine conformational isomerisation which would give atropisomers **(Figure 44)**. However another possibility is

minor peaks is as a consequence of chirality at CHR$_1$ group which gives isomers because of the different configurations at metal which do not epimerise thus crystals could be mixed **(Table 19)**.

Figure caption:
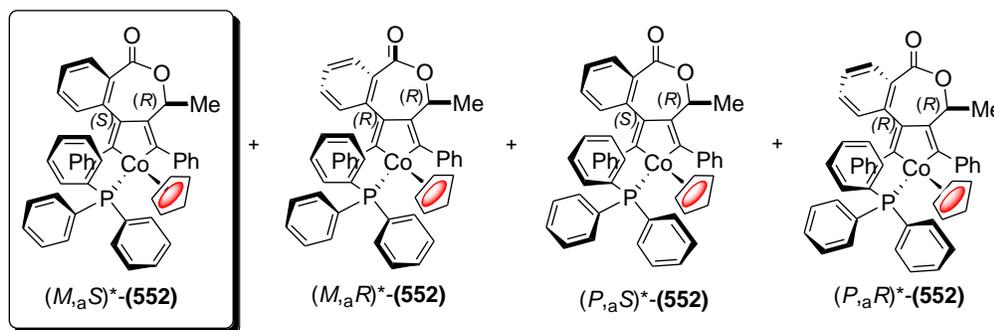
Figure 44. Theoretical model with defined relative configuration, dynamic equilibrium and the suspected complexes in solution state.

Table 19. Shows the isomer distribution for each lactone complexes synthesised.

Complex	Entry	R$_1$	R$_2$	R$_3$	R$_4$	R$_5$	d.r (^{1}H NMR, CDCl$_3$)
(552)	1	Me	Ph	H	Ph	H	11:1:1:1
(553)	2	H	Ph	H	Ph	H	2:1:0:0
(555)	4	Me	p–CF$_3$C$_6$H$_4$	H	Ph	H	17:1:1:1
(556)	5	Me	Ph	H	p–CF$_3$C$_6$H$_4$	H	11:1:1:1
(557)	6	Me	p–CF$_3$C$_6$H$_4$	H	p–CF$_3$C$_6$H$_4$	H	15:1:1:0
(558)	7	i–Pr	Ph	H	Ph	H	1:0:0:0
(559)	8	t–Bu	Ph	H	Ph	H	18:5:2:0
(560)	9	Me	n–Bu	H	Ph	H	1:0:0:0
(563)	10	Me	Ph	H	3–NC$_5$H$_4$	H	10:2:1:1
(564)	11	Me	Ph	H	o–OCH$_3$C$_6$H$_4$	H	13:1:1:1
(566)	12	Me	o–Br C$_6$H$_4$	H	Ph	H	7:2:2:1
(567)	13	Me	2–Cl–4–pyridyl	H	Ph	H	8:1:1:1
(568)	14	Me	Ph	H	Ph	CO$_2$Me	13:1:1:1
(571)	15	Me	Ph	H	p–CF$_3$C$_6$H$_4$	CO$_2$Me	9:2:1.5:1
(572)	16	Me	p–CF$_3$C$_6$H$_4$	H	Ph	CO$_2$Me	10:2:1:0

The substitution of R$_1$= Me (S$_C$,R$_{Co}$,P)*–**(552)** with R$_1$=i–Pr (S$_C$,R$_{Co}$,P)*–**(558)** not only results in a significantly better yield but also only one isomer was detected by ^{1}H NMR spectroscopy. However, when R$_1$= t–Bu three isomers are observed. This result was considered to be as a consequence of steric clashes as the t–Bu functionality is significantly larger with respect to a cone angle than an isopropyl substituent. When R$_2$= p–CF$_3$C$_6$H$_4$ (S$_C$, R$_{Co}$, P)*–**(555)**, the minor peaks were smaller then with R$_4$= p–CF$_3$C$_6$H$_4$ (S$_C$,R$_{Co}$,P)*–**(556)**. A longer chained aliphatic group R$_2$= n–Bu **(560)** appeared not to give any minor peaks. Lactone complexes (S$_C$,R$_{Co}$,P)*–**(566)** and (S$_C$,R$_{Co}$,P)*–**(567)** which are both *ortho* substituted showed a lower selectivity. **(553)** was very interesting as only a d.r.= 2:1 was observed this implied one of two important possibilities they are the diastereomeric ratio is a consequence of axial chirality and propeller conformational chirality (2^2= 4 stereoisomers therefore suggests two diastereoisomers) or which is less likely based on the information from the other lactone systems is that the diastereomeric ratio could be as a result of chiral–at–metal

and propeller conformational chirality which would coincidently also give two diastereoisomers and four stereoisomers in total.

Entries 14–16 of **Table 19** present selected examples of diastereomeric ratio in the solution state when R_5= CO_2Me. In some cases the selectivity is improved but in others it is worse. Hence it is not possible to explain or predict the effect of CO_2Me substituent on the Cp. But comparing entry 5 and 15, 15 is less selective. The *d.r.* indicates there is an electronic and steric influence that this group has on diastereomeric ratio relative to its non R_5= CO_2Me substituted counterparts.

To support the contention that the configuration of the metal centered element of chirality was left intact, (*S*)–(–)–3–butyn–2–ol was used in a chiral synthesis of (S_C,R_{Co},*P*)–**(552)** **(Scheme 115)**. Using analytical HPLC, both chiral–at–cobalt lactone complexes of **(552)** were assigned to their retention times. The HPLC output indicated; R_t= 30 min 30 sec for the S_C–enantiomer and R_t=34 min 48 sec for the R_C–enantiomer {HPLC (CHIRALCEL OD) 96.5:3.5 hexane/isopropyl alcohol, 1 mL/min}. The HPLC trace for the enantiopure chiral–at–cobalt (S_C,R_{Co},*P*)–**(552)** was R_t=26 min 42 sec (*S*–enantiomer). Assignments were accurately made by enriching (spiking) the racemic sample with the enantiopure isomer, the enantiopurity of (*S*)–**(345)** was checked and only one peak was present (**Table 20, 21** and **Figure 45, 46**).

Scheme 115. Enantiopure synthesis of (S_C,R_{Co},*P*)–**(552)**.
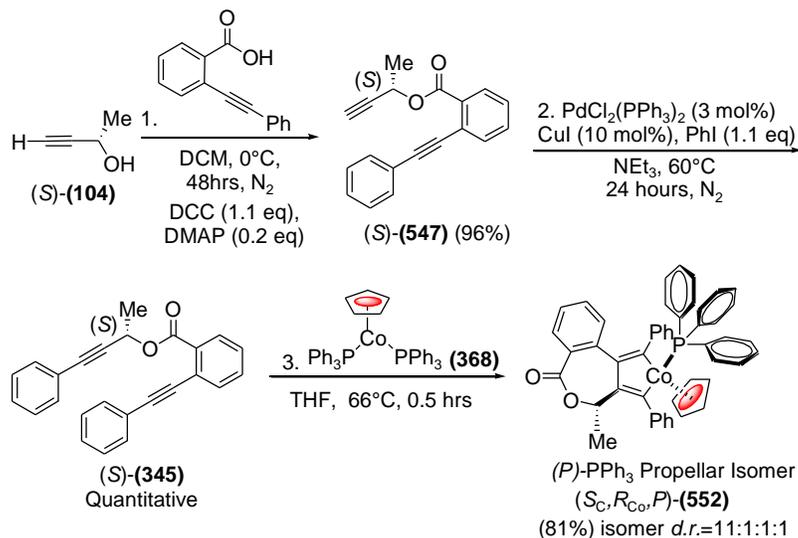
Table 20. Peak table for the enantiopure system (S_C,R_{Co},P)–**(552)** (Ch1254 nm).

Peak	Ret. Time (min: sec)	Area	Height	Peak Start (min: sec)	Peak End (min: sec)	Area%
1	26:48	6658845	44789	24:48	32:24	94.4
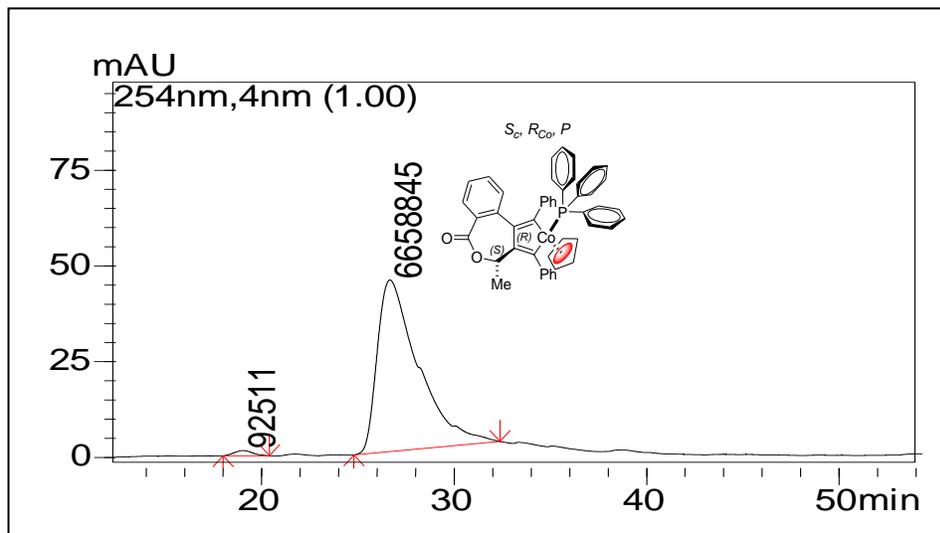
Figure 45. Chromatogram of (S_C,R_{Co},P)–**(552)**.

Table 21. Peak table for the racemic system (S_C,R_{Co},P)*–**(552)** (Ch1254 nm).

Peak	Ret. Time (min: sec)	Area	Height	Peak Start (min: sec)	Peak End (min: sec)	Area%
1	30:30	1345097	11213	29:00	33:18	46.2
2	34:48	1468029	11991	33:18	39:30	50.5
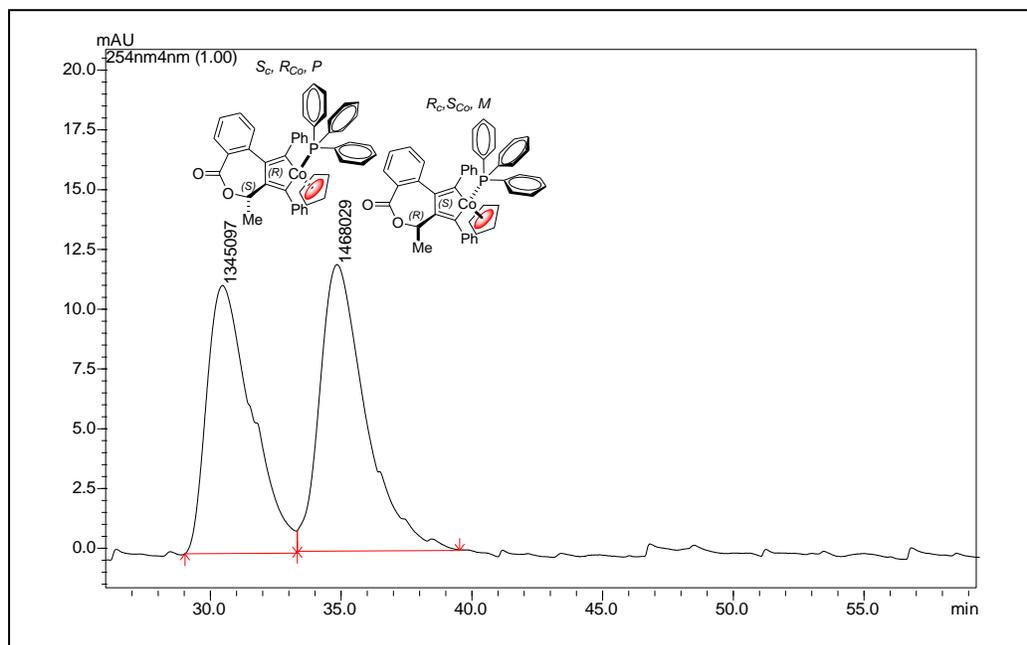
Figure 46. Chromatogram of (S_C,R_{Co},P)–**(552)** and (R_C,S_{Co},M)–**(552)**.

It was hoped that heating the parent lactone complex (S_C,R_{Co},P)*–**(552)** would convert into a chiral η⁴–cyclobutadiene metallocene **(Scheme 116)**. However, using a variety of reaction conditions and careful monitoring of the reaction a [2+2] cyclodimerisation process could not be induced. In each attempt, there appeared to be a competing pathway that decomposed (S_C,R_{Co},P)*–**(552)**. Although the starting material appeared to be consumed, the products it gave were non metallocene like and difficult to identify. In order to try and lower the free energy required for this [2+2] cyclodimerisation process, DIBAL–H was used to ring open the lactone. Astonishingly, an intermolecular Meerein–Pondorf–Verley (MPV) [206] β–hydride shift occurred *via* a six–membered transition state **(Figure 47)** and **(576)** was isolated in 42% **(Scheme 117)**. To support the identity of this compound the ¹H NMR spectrum showed a downfield shift of the methyl group from δ1.12 ppm (3H, d, *J* 6.9 Hz, CH_3) in **(552)** to δ1.49 ppm (3H, s, CH_3) in **(576)**. The methylene protons were diastereotopic being observed at δ 4.14 ppm (1H, d, *J* 8.1 Hz, CH_2) and δ 4.86 ppm (1H, d, *J* 8.1 Hz, CH_2). The ¹³C NMR spectrum showed peaks that were downfield relative to the starting material at δ 30.9 (CH_3) and δ 64.7 (CH_2) indicating they are deshielded, as well as at δ 202.7 ppm (*CO*). A ³¹P NMR spectrum gave a single peak at δ 53.5 ppm which is higher than the starting material **(552)** at δ 49.3 ppm. An IR spectra of the sample showed a broad stretch at 3200 cm⁻¹ (OH) which was not present in the starting material and 1662 cm⁻¹ (C=O).
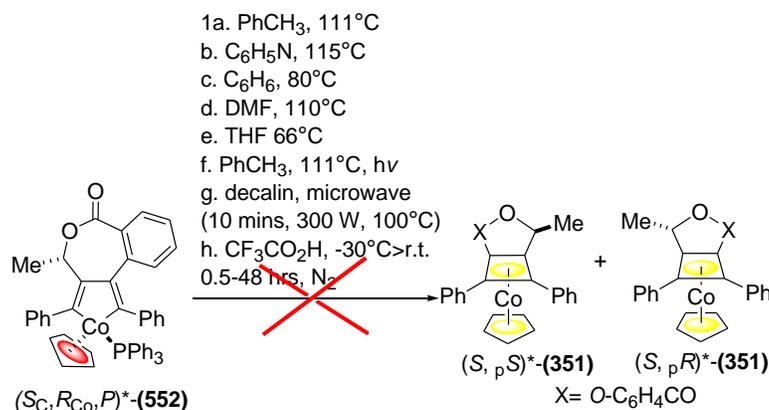
Scheme 116. Attempted synthesis of planar chiral η⁴–cyclobutadiene metallocenes **(351)**.
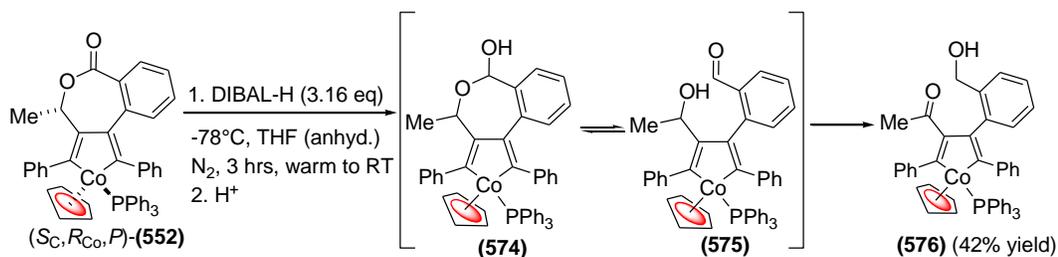
Scheme 117. Intermolecular Meerein–Pondorf–Verley (MPV) hydride shift.
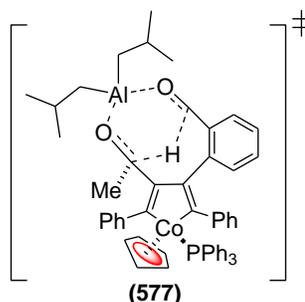
(577)
Figure 47. Transition state and β–hydride shift in the Meerein–Pondorf–Verley (MPV) reaction.

Subsequent heating of complex **(576)** resulted in the planar chiral η^4–cyclobutadiene metallocene **(578)** in 99% yield **(Scheme 118)**. This compound was a distinctive yellow solid with a melting point of 150–152°C. The ^{1}H NMR spectrum of this compound showed peaks at δ 1.87 ppm (3H, s, CH_3) and δ 2.10 ppm (1H, brs, OH) and also diastereotopic methylene protons at δ 4.32 ppm (1H, d, *J* 8.1 Hz, CH_2) and δ 4.45 ppm (1H, d, *J* 8.1 Hz, CH_2). The aromatic region was significantly clearer and integrated for exactly 14 protons. IR spectroscopy suggested the presence of a hydroxy group at 3200 cm^{-1} and carbonyl group at 1700 cm^{-1}. The ^{13}C NMR spectrum showed a peak at δ 202.2 ppm (*CO*). Elemental analysis of the sample found C, 75.60% and H, 5.35% compared with calculated values of C, 75.63% and H, 5.29% for $C_{30}H_{25}CoO_2$. The reaction that gave **(576)** could not be repeated although many attempts were made.
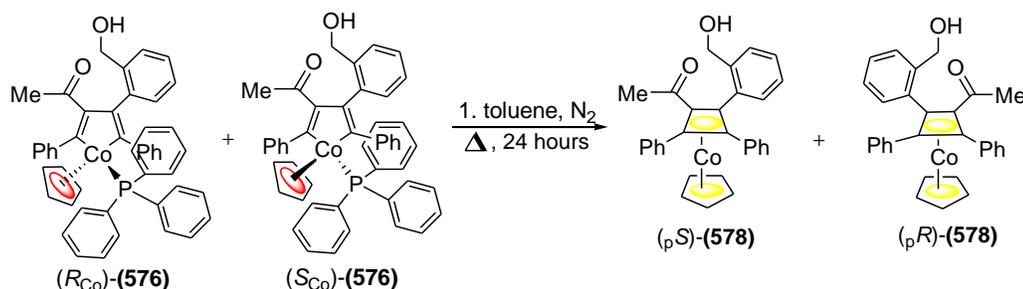
Scheme 118. Synthesis of η^4–cyclobutadiene metallocene **(578)**.

3.2.7 Synthesis of 5,5–membered Cyclic Ether Complexes.

Oxidative cyclisation of the ether bridged diyne (*rac*)–**(343)** using 1 equiv. of CoCl(PPh$_3$)$_3$ **(100)** and 1.1 equiv. of Na(C$_5$H$_5$) **(486)** gave two inseparable diastereoisomers in 39% yield. The integrals of both diastereoisomers suggested a diastereomeric ratio of 3:2. To identify the relative stereochemistry of both isomers and to assign the spectroscopic data the sample was recrystallised and X–ray quality crystals were obtained. **Figure 48** shows the crystal structure of (S_C,R_{Co},M)*–**(579)**. The actual crystal used to obtain the crystal structure when dissolved in CDCl$_3$ showed a *d.r.* =19:1 {^{1}H NMR; δ 4.77: δ 4.65 ppm}. Repeating this reaction with 1.4 equiv. of CoCl(PPh$_3$)$_3$ and 1.4 equiv. of Na(C$_5$H$_5$) (2 M in THF) gave a 70% yield with a *d.r.* = 2:3 {(S_C,R_{Co},M)*: (S_C,R_{Co},P)*} in favour of the other isomer. Using 1 equivalent of (η^5–cyclopentadienyl)*bis*(triphenylphosphine)cobalt(I) and 1 equiv. of (*rac*)–**(343)** gave a diastereomeric ratio of 2:3 in 87% yield. **Table 22** is a spectroscopic comparison of key NMR parameters of both isomers **(Scheme 119)**.
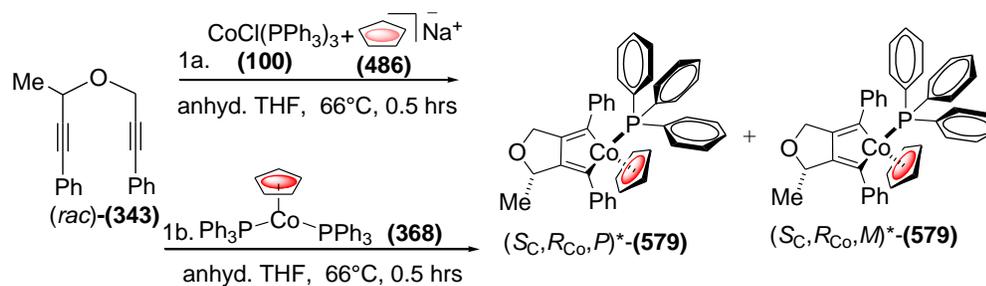
Scheme 119. Synthesis of 5,5–membered cyclic ether complex **(579).**

Table 22. Spectroscopic characterisation of isomers **(579)**.

δ_H ^{1}H NMR (δ, 270 MHz, CDCl$_3$)	
(S_C,R_{Co},P^*)–**(579)**	(S_C,R_{Co},M^*)–**(579)**
0.45 (3H, d, *J* 6.2 Hz, C*H*$_3$)	0.76 (3H, d, *J* 6.2 Hz, C*H*$_3$)
4.65 (5H, s, C$_5$*H*$_5$)	4.77 (5H, s, C$_5$*H*$_5$),
δ_C ^{13}C NMR (δ 67 MHz, CDCl$_3$)	
20.1 (*C*H$_3$)	20.1 (*C*H$_3$)
88.8 (*C*$_5$H$_5$)	88.1 (*C*$_5$H$_5$),
δ_P ^{31}P NMR (δ, 109 MHz, CDCl$_3$);	
53.2 (*P*Ph$_3$)	52.6 (*P*Ph$_3$)
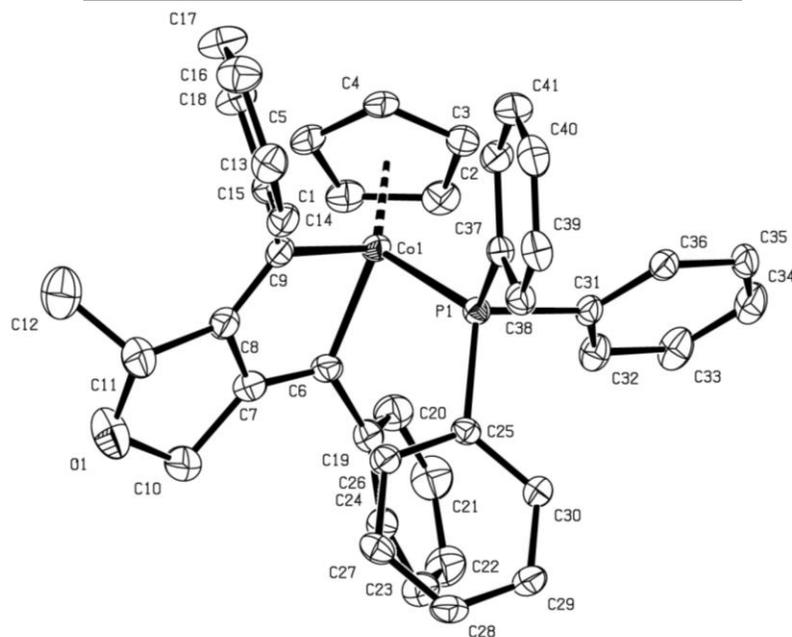
Figure 48. Molecular structure and atom numbering scheme for (S_C,R_{Co},M^*)–**(579)** with 50% displacement ellipsoids, all H atoms are omitted for clarity. Selected bond distances (Å) and angles (°): C(9)–Co(1) 1.994(3), C(6)–Co(1) 1.993(3), C(6)–C(7) 1.347(5), C(7)–C(8) 1.451(5), C(8)–C(9) 1.345(4), Co(1)–P(1) 2.1663(9), C(10)–O(1)–C(11) 112.9(3), C(6)–Co(1)–P(1) 92.25(9) .

The effect of the presence of a CO$_2$Me moiety on the cyclopentadienyl ring was investigated **(Scheme 120)**. In an oxidative cyclisation, isomers of **(580)** were synthesised in 77% yield with a diastereomeric ratio of 2:1. The spectroscopic data of **(580)** showed methyl peaks at δ 0.31 (3H, d, *J* 6.2 Hz, (major)–C*H*$_3$) and δ 0.71 (3H, d, *J* 6.2 Hz,

(minor)–CH_3) and at δ 3.50 ppm (3H, s, (major)–OCH_3) and δ 3.66 ppm (3H, s, (minor)–OCH_3). IR spectroscopy showed a carbonyl stretch at 1717 cm^{-1} (C=O).
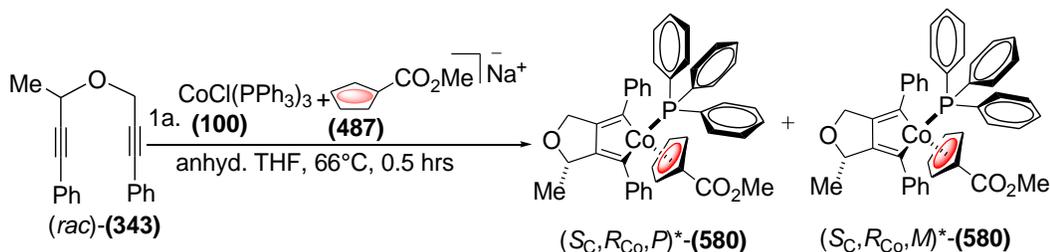
Scheme 120. Synthesis of 5,5–membered cyclic ether complexes containing a carbomethoxycyclopentadienyl group.

To support the theory of propeller isomers, achiral–at–cobalt and chiral–at–cobalt 5,5–membered cyclic ether complexes were synthesised **(581)** and **(582)**. Ether bridged 5,5–membered cyclic ether complexes **(581)**–**(586)** using method 1a was not detected (**Scheme 121**, **Table 23**).
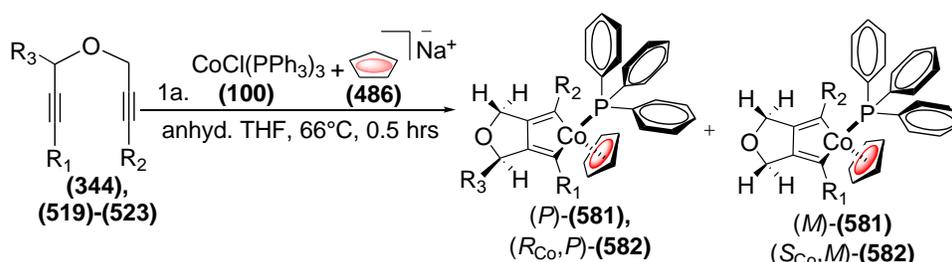
Scheme 121. Synthesis of achiral 5,5–membered cyclic ether complexes.

Table 23. Experimental results for the synthesis of 5,5–membered cyclic ether complexes.

Diyne	Compound	Entry	R$_1$	R$_2$	R$_3$	Yield (%)$^{(a)}$	Conformational isomer distribution
(519)	**(581)**	1	C$_6$H$_5$	C$_6$H$_5$	H	1a: 69%	e.r.= 1:1, $^{(c)}$
(522)	**(582)**	2	C$_6$H$_5$	p–C$_6$H$_4$F	H	1a: 67%	d.r.= 4:1 $^{(a), (b)}$
(521)	**(583)**	3	C$_6$H$_5$	p–C$_6$H$_4$OCH$_3$	H	–	–
(523)	**(584)**	4	C$_6$H$_5$	p–C$_6$H$_4$CF$_3$	Me	–	–
(520)	**(585)**	5	C$_6$H$_5$	2, 6–(CH$_3$)$_2$C$_6$H$_3$	H	–	–
(344)	**(586)**	6	C$_6$H$_5$	Ph	i–Pr	–	–

$^{(a)}$. After column chromatography. $^{(b)}$. Determined by ^{1}H NMR spectroscopy (400 MHz, CDCl$_3$). $^{(c)}$. Determined by chiral HPLC.

Spectroscopic evidence which supported the synthesis of **(581)** includes a ^{1}H NMR spectrum which showed roofing for the methylene protons at δ 3.80 ppm (2H, d, *J* 18.5 Hz, CH_2) and δ 4.22 ppm (2H, d, *J* 18.5 Hz, CH_2). At δ 5.62 ppm (5H, s, C$_5$$H_5$) a singlet was found to integrate for five protons. The ^{13}C NMR spectrum gave peaks at δ 68.4 ppm (CH$_2$) and δ 88.1 ppm (C$_5$H$_5$). ^{31}P NMR spectroscopy showed a peak at δ 56.4 ppm. Analytical chiral HPLC gave two peaks which are thought to be the *P* and *M* conformational isomers of triphenylphosphine (**Figure 49, Table 24**). The retention time for the peaks were R$_t$= 22 min 6 sec and R$_t$= 38 min 6 sec {HPLC (CHIRALCEL OD) 99:1 hexane/isopropyl alcohol, 0.5 mL/min}.
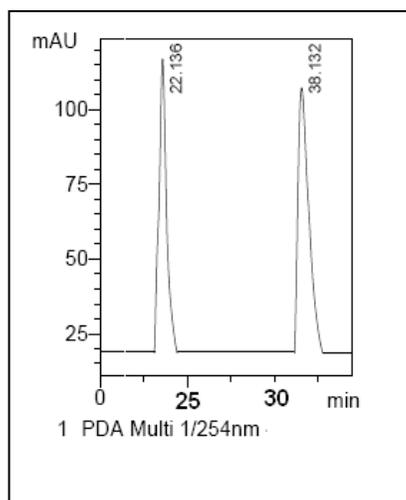
Figure 49. HPLC output of achiral–at–cobalt complex **(581)**.

Table 24. Peak table for **(581)** (Ch1254 nm).

Peak	Ret. Time (min:sec)	Area	Height	Peak Start (min:sec)	Peak End (min:sec)	Area%
1	22:06	9300027	114289	21:06	25:30	49.6
2	38:06	9454781	99728	37:06	40:54	50.4

HPLC (CHIRALCEL OD) 99:1 hexane/isopropyl alcohol, 0.5 mL/min.

With respect to the chiral–at–cobalt complex **(582),** spectroscopic analysis of the sample indicated a diastereoselective complexation. In the absence of central chirality at carbon this was thought to be due to the conformational phosphine isomers and the chiral metal centre. The ^{1}H NMR spectrum showed broad singlets for methylene protons at δ 3.82 ppm (2H, brs, (major)–CH_2) and at δ 4.24 ppm (2H, brs, (major)–CH_2). Using correlation spectroscopy (HMQC) these methylene protons were found to correspond to peaks at δ 68.3 and δ 60.6 ppm in the ^{13}C NMR spectrum. The cyclopentadienyl moiety was correlated from δ 4.70 {5H, s, (major)–C$_5$H$_5$} in the ^{1}H NMR spectrum to δ 88.1 ppm {(major)–C$_5$H$_5$}, respectively. A minor isomer was also detectable, at δ 4.60 ppm {5H, brs, (minor)–C$_5$H$_5$} was correlated to δ 89.4 ppm {(minor)–C$_5$H$_5$} on the ^{13}C NMR spectrum. The methylene protons were correlated from δ 60.9 (CH_2) to δ 3.60 (2H, brs, (minor)–CH_2) and the second although overlapping in the proton NMR spectrum with the minor–C$_5$H$_5$ was correlated to δ 85.5 ppm in the ^{13}C NMR spectrum. One broad peak in the ^{31}P NMR spectrum at δ 56.3 ppm and two peaks in the ^{19}F NMR spectrum at δ –119.1 ppm (major) and δ –120.1 ppm (minor) were also detected. Elemental analysis was satisfactory.

Analytical chiral HPLC was used to support the theory of two metal–centred diastereoisomers **(Figure 50, Table 25)**. However, only three peaks were resolved from the expected four. The peak which has a retention time of 23:0 mins is assumed to have both minor isomers.
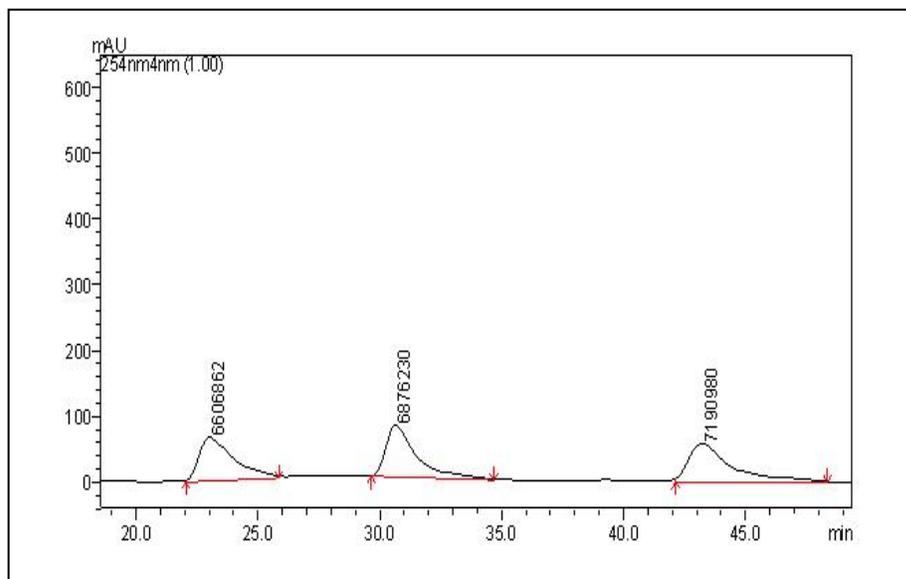
Figure 50. HPLC output of achiral–at–cobalt complex **(582)**.

Table 25. Peak table for **(582)** (Ch1254 nm).

Peak	Ret. Time (min:sec)	Area	Height	Peak Start (min:sec)	Peak End (min:sec)	Area%
1	23:00	6606862	66112	22:00	26:54	32.0
2	30:36	6876230	78287	29:42	34.42	33.3
3	43:12	7190980	58243	42:06	48:24	34.8

HPLC (CHIRALCEL OD) 99:1 hexane/ isopropyl alcohol, 0.5 mL/min.

Chiral synthesis of **(579)** was accomplished using the commercially available enantiopure propargylic alcohol (*S*)–3–butyn–2–ol **(104)**. Protecting group chemistry was used to synthesise (*S*)–**(585)** and (*S*)–**(586)** the latter in higher yield**.** The Ph$_2$*t*–BuSi protecting group **(584)** gave quantitative yield prior to Sonogashira cross coupling to (*S*)–**(391)** {[α]$_D$ = –49.0 (*c* 1.0 , 26.7°C, dioxane)}. Using the established route to synthesis of the racemic diyne ethers, (*S*)–**(343)** was synthesised in 99% yield {[α]$_D$ = –281.7 (*c* 0.014, 23.2°C, CHCl$_3$)}. The enantiopurity just after complexation was checked using analytical HPLC and optical rotation, the stereochemical integrity of the molecules were found to be consistent.

In a [2+2] oxidative cyclisation reaction 1 equiv. of (η^5–cyclopentadienyl)*bis*(triphenylphosphine)cobalt and 1 equiv. of (*S*)–**(343)** heated to reflux for 30 mins gave diastereoisomers of **(579)** with a *d.r.*=1:1 in 96% overall yield **(Scheme 122)**. Recrystallisation gave a diastereomeric ratio of 6:1 in favour of (*S*$_C$,*R*$_{Co}$,*M*)–**(579)** isomer. Spiking experiments using racemic and enantio enriched samples of **(579)** allowed the stereochemistry to be assigned to the peak retention times determined using chiral HPLC **(Figure 51**, **52** and **53 Table 26**, **27** and **28)**.
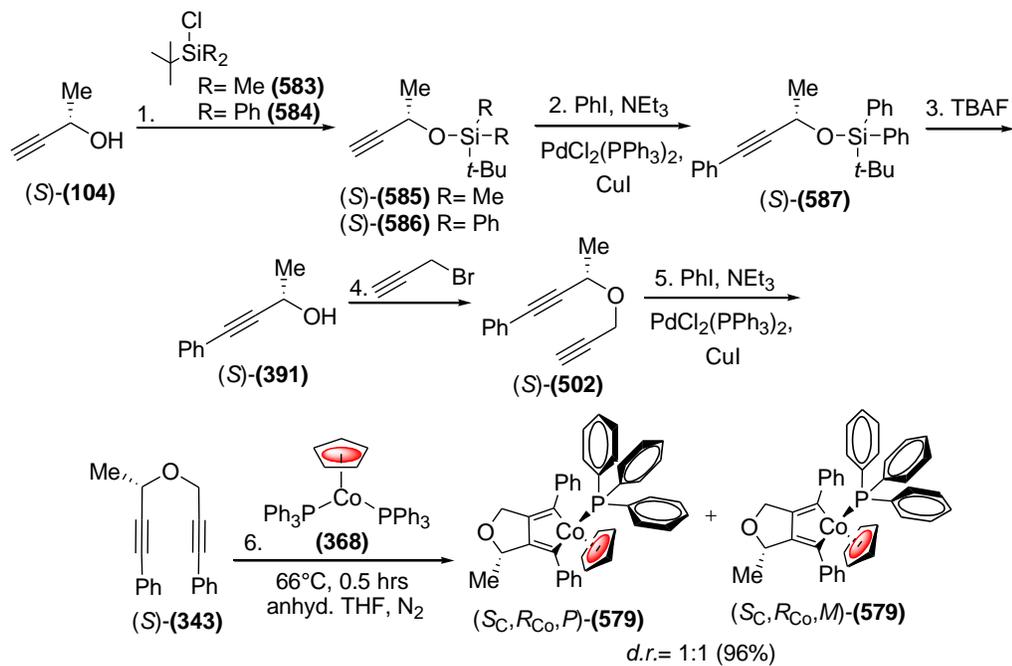
Scheme 122. Synthesis of 5,5–membered cyclic ether complex **(579)**.
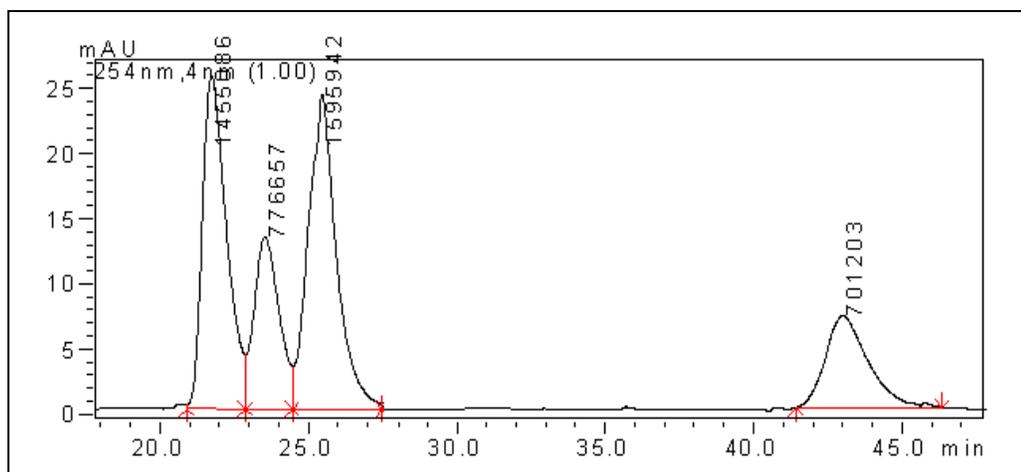
Figure 51. Chromatogram of (*rac*)–**(579)** *d.r.* = 3:2.

Table 26. Peak table for racemic complex **(579)** *d.r.*= 3:2 (Ch1254 nm).

Peak	Ret. Time (min:sec)	Area	Height	Peak Start (min:sec)	Peak End (min:sec)	Area%	Complex
1	21:42	1455086	25455	20:54	22:54	30.0	(R_C,S_{Co},M)–**(579)**
2	23:30	776657	13209	22:54	24:30	16.0	(S_C,R_{Co},P)–**(579)**
3	25:30	1595942	24145	24:30	27:30	39.4	(S_C,R_{Co},M)–**(579)**
4	43:00	701203	7044	41:24	46:24	14.5	(R_C,S_{Co},P)–**(579)**

HPLC (CHIRALCEL OD) 99.6:0.4 hexane/ isopropyl alcohol, 0.5 mL/min.
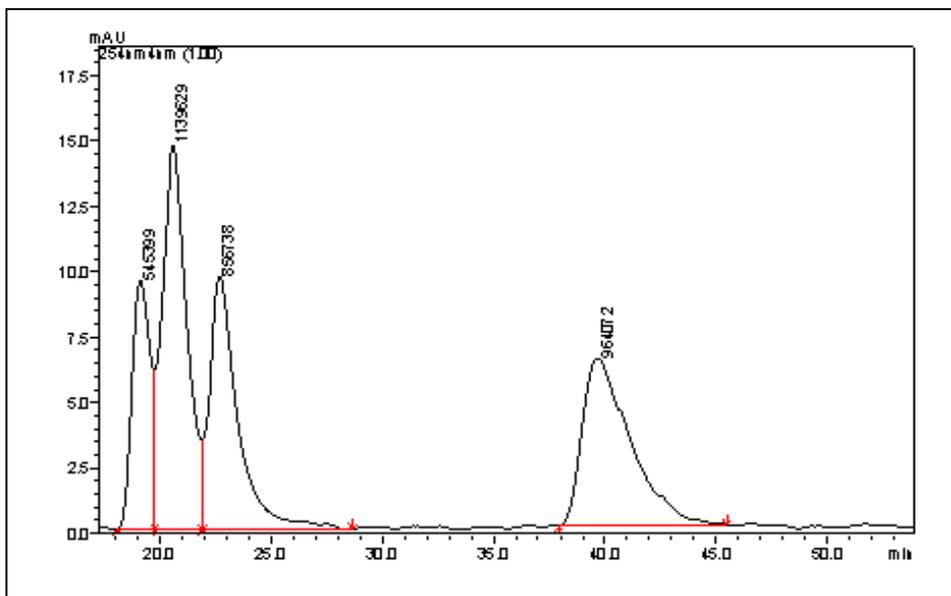
Figure 52. Chromatogram of (*rac*)–**(579)** *d.r.*= 2:3.

Table 27. Peak table for racemic complex **(579)** *d.r.*= 2:3 (Ch1254 nm).

Peak	Ret. Time (min:sec)	Area	Height	Peak Start (min:sec)	Peak End (min:sec)	Area%	Complex
1	19:06	545399	9512	18:06	19:48	15.6	(R_C,S_{Co},M)–**(489)**
2	20:36	1139629	14730	19:48	21:54	32.5	(S_C,R_{Co},P)–**(489)**
3	22:42	856738	9683	21:54	28:42	24.4	(S_C,R_{Co},M)–**(489)**
4	39:42	964072	6397	38:00	45:30	27.5	(R_C,S_{Co},P)–**(489)**

HPLC (CHIRALCEL OD) 99.6/0.4 hexane/ isopropyl alcohol, 0.5 mL/min.
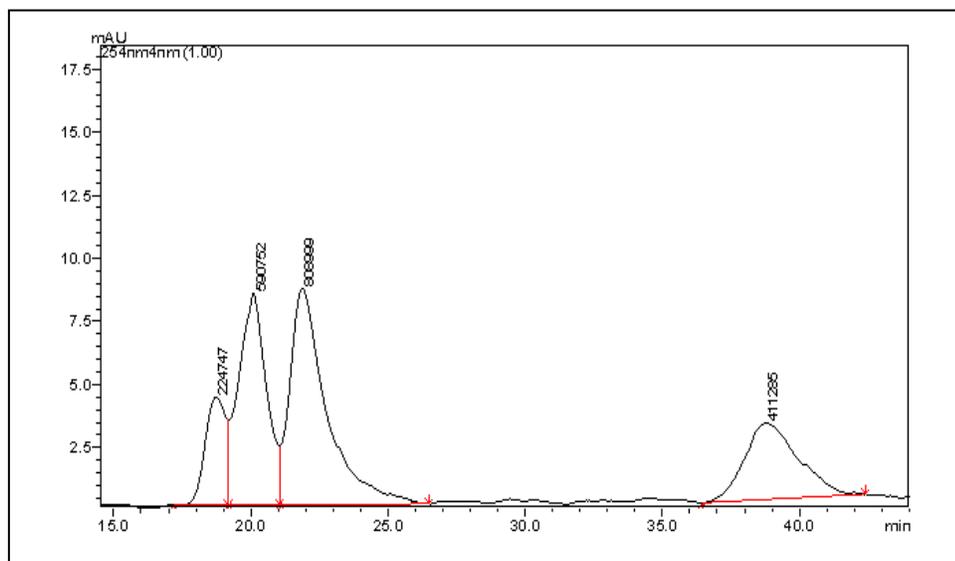
Figure 53. Chromatogram of chiral–at–cobalt **(579)** *d.r.*= 2:3 enantioenriched 6:1.

Table 28. Peak table for racemic complex **(579)** *d.r.*= 2:3 enantioenriched 6:1 (Ch1254 nm).

Peak	Ret. Time (min:sec)	Area	Height	Peak Start (min:sec)	Peak End (min:sec)	Area%	Complex
1	18:42	224747	4288	17:12	19:12	11.0	(R_C, S_{Co}, M)–**(579)**
2	20:06	590752	8395	19:12	21:00	29.0	(S_C, R_{Co}, P)–**(579)**
3	21:54	808999	8554	21:00	26:30	39.7	(S_C, R_{Co}, M)–**(579)**
4	38:48	411285	3020	36:30	42:24	20.2	(R_C, S_{Co}, P)–**(579)**

HPLC (CHIRALCEL OD) 99.6/0.4 hexane/ isopropyl alcohol, 0.5 mL/min.

Using (*rac*)–**(579)** and applying reaction conditions 1a–d **(Scheme 123)** a diastereoselective synthesis of **(351)** was attempted. Following the progress of the reaction by ^{1}H NMR and TLC, it was apparent that the starting material was being consumed but no characteristically 'yellow' η^4–cyclobutadiene metallocene was being formed. Instead a fine black paramagnetic precipitate was observed.
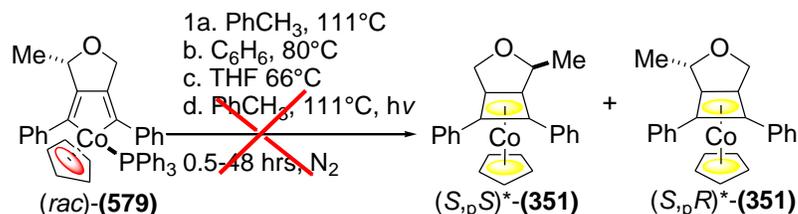
Scheme 123. Attempted diastereoselective synthesis of chiral η^4–cyclobutadiene metallocene **(351)**.

Heating 5 mg of the enantio enriched (S_C, R_{Co}, M)–**(579)** at 60°C in anhyd. THF (1 mL) for 2 hours allowed the kinetics of epimerisation at phosphine to be determined using HPLC (CHIRALCEL OD) **(Scheme 124, Table 29–32)**. **Figure 54** illustrates the decrease in the concentration of (S_C, R_{Co}, M)–**(579)** over time. The rate constant (k or λ) was calculated using the half life $t_{1/2}$= 2640 mins (44 hours), k=ln2/ $t_{1/2}$= 4.38 x 10^{-6} s^{-1}.
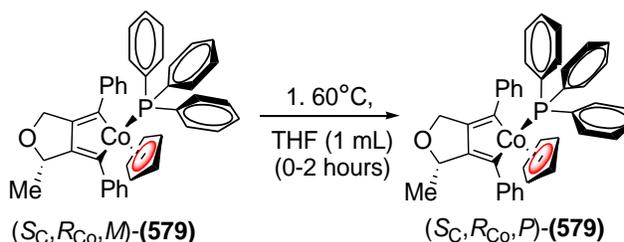
Scheme 124. Configurational isomerism in **(579)**.
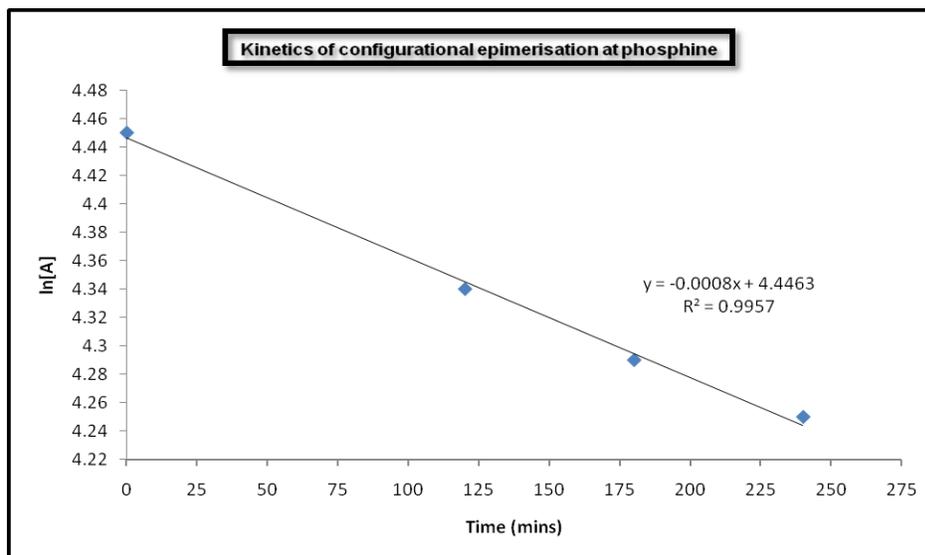
Figure 54. Reaction kinetics of (S_C,R_{Co},M)–**(579)**.

Table 29. Reaction kinetics of epimerisation (0 mins).

Peak	Ret. Time (min:sec)	Area	Height	Peak Start (min:sec)	Peak End (min:sec)	Area%	ln[A]
1	20:18	104476	1750	19:24	21:06	14.3	2.66
2	22:12	624438	7422	21:06	25:36	85.7	4.45

99.5% Hexane, 0.5% IPA, 120 min, 0.5 mL/min

Table 30. Reaction kinetics of epimerisation (120 mins).

Peak	Ret. Time (min:sec)	Area	Height	Peak Start (min:sec)	Peak End (min:sec)	Area%	ln[A]
1	49:42	1756430	9556	46:12	52:06	23.0	3.14
2	54:48	5881686	33958	52:06	59:06	77.0	4.34

99.5% Hexane, 0.5% IPA, 120 min, 0.5 mL/min

Table 31. Reaction kinetics of epimerisation (180 mins).

Peak	Ret. Time (min:sec)	Area	Height	Peak Start (min:sec)	Peak End (min:sec)	Area%	ln[A]
1	49:18	2223485	11538	45:36	51:42	26.9	3.29
2	54:30	6041868	33362	51:42	58:54	73.1	4.29

99.5% Hexane, 0.5% IPA, 120 min, 0.5 mL/min

Table 32. Reaction kinetics of epimerisation (240 mins).

Peak	Ret. Time (min:sec)	Area	Height	Peak Start (min:sec)	Peak End (min:sec)	Area%	ln[A]
1	35:30	10971678	115998	33:30	36:24	29.2	3.37
2	37:54	26592152	240141	36:24	40:12	70.8	4.26

99.5% Hexane, 0.5% IPA, 120 min, 0.5 mL/min

To establish if epimerisation was as a result of phosphine dissociation 0.15 mmol of enantioenriched **(579)** was reacted with 1 equiv. of *tris*(*p*–tolyl)phosphine and heated at 60°C in anhyd. THF (1 mL) for 7 hours **(Scheme 125)**. The kinetics of the reaction were followed using analytical HPLC (CHIRALCEL OD) **(Figure 55)** $t_{1/2}$= 270 mins, k=ln2/$t_{1/2}$= 0.043 x 10^{-3} s^{-1}. **Figure 56**, shows a HPLC trace after three hours of stirring. The chromatogram shows two new albeit over lapping peaks (**Table 33**, peak 1, 2), they are thought to be a 1:1 ratio of configurational isomers of *tris*(*p*–tolyl)phosphine.

The crude ^{1}H NMR spectrum supported the synthesis of this new adduct **(588)** as doublets were observed at δ 0.90 ppm (3H, d, *J* 6.4 Hz, C*H$_3$*) and δ 1.01 (3H, d, *J* 6.4 Hz, C*H$_3$*) and at δ 2.26 ppm (9H, s, {P(*p*–CH$_3$C$_6$H$_4$) }$_3$ and at δ 2.33 ppm (9H, s, {P(*p*–CH$_3$C$_6$H$_4$) }$_3$ due to the signal for the methyl groups of the *p*–tolyl groups. Also the η^5–C$_5$H$_5$ signals were observed at δ 4.55 ppm (5H, s, C$_5$*H$_5$*) and δ 4.59 ppm (5H, s, C$_5$*H$_5$*). Efforts to purify the new adduct using conventional column chromatography (3:7, 1:19 ethyl acetate/hexane) failed because the R$_f$ of both the compounds were the same, crystallisation (1:19 EtOAC/hexane) was unsuccessful as they did not crystallise **(Scheme 125)**.
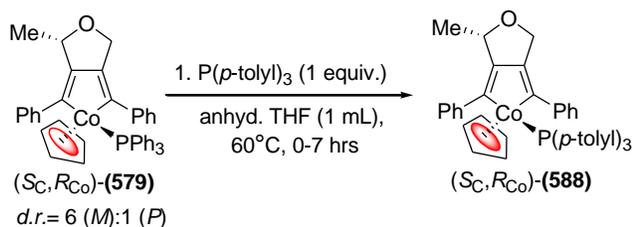
Scheme 125. Phosphine exchange experiment.
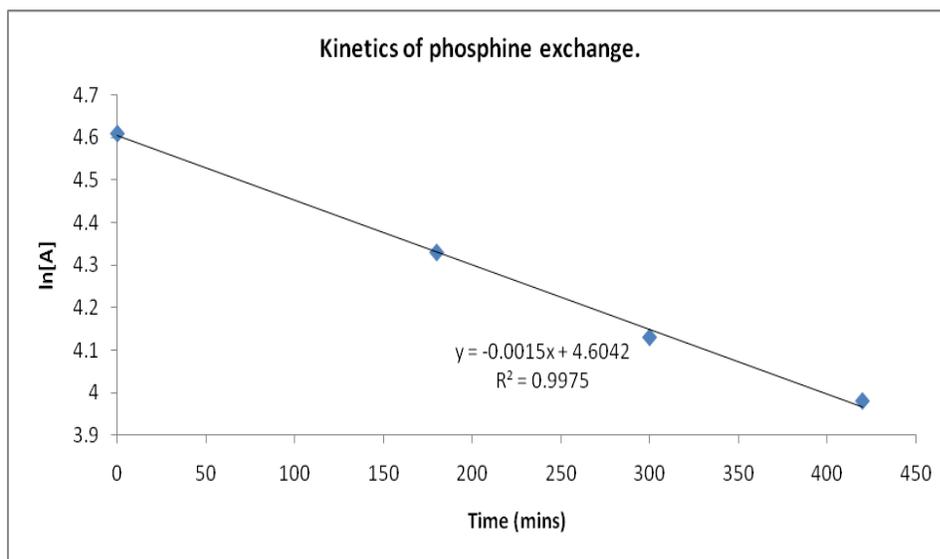
Figure 55. Kinetics of phosphine exchange using enantio enriched **(579)** to **(588)**.
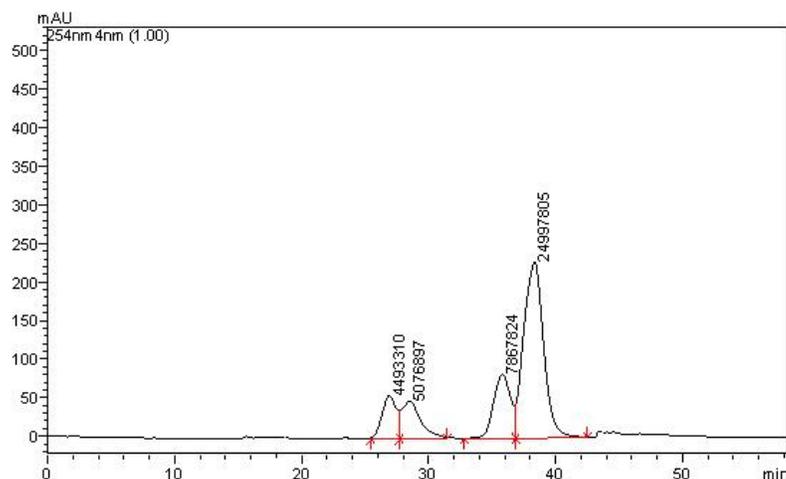
Figure 56. Typical HPLC output (after 180 mins).

Table 33. Peak Table of HPLC data at 180 mins (Ch1254 nm).

Peak	Ret. Time (min:sec)	Area	Height	Peak Start (min:sec)	Peak End (min:sec)	Area%
1	26:54	4493310	56546	25:30	27:42	10.6
2	28:30	5076897	49385	27:42	31:24	12.0
3	35:48	7867824	82801	32:48	36:54	18.5
4	38:18	24997805	228910	36:54	42:30	58.9

RT, 99% Hexane, 1% IPA, 70 mins, 0.5 mL/ min, after 3 hours heating at 60°C in THF (1 mL) with 1 equiv. of (*p*–tolyl)$_3$P.

The enantio enriched sample of **(579)** *d.r.*= 6:1 which was in favour of (S_C,R_{Co},*M*)–**(579)** and the lactone complex (S_C,R_{Co},*P*)–**(552)** were further studied using circular dichromism. Circular dichromism spectroscopy (UV–Vis) was used to measure the absorption of left–handed polarised light versus right handed polarised light arising from asymmetry in each complex.[207] Enantio enriched (S_C,R_{Co},*M*)–**(579)** gave a positive value at 520 nm (conc.= 0.18 mM) **(Figure 57)**, whilst (S_C,R_{Co},*P*)–**(552)** at 500 nm (conc. = 0.40 mM) gave a negative value **(Figure 58)**. Both results complemented their polarometry readings *i.e.* [α]$_D$ = +762.6 (*c* 0.0015, 23.5°C, CHCl$_3$) for the enantioenriched ether complex **(579)** and [α]$_D$ = –746.0 (*c* 0.002, 22.8°C, CHCl$_3$) for the lactone complex **(552)**.
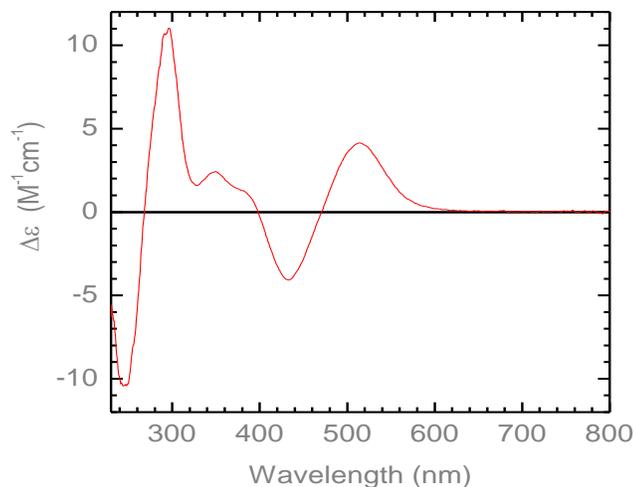
Figure 57. UV–Vis spectrum of metallocyclopentadiene complex S_C,R_{Co},M–**(579)**.
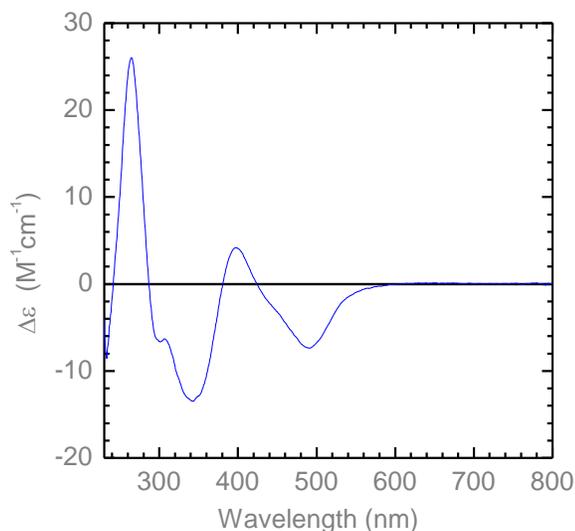
Figure 58. UV–Vis spectrum of metallocyclopentadiene complex S_C,R_{Co},P– **(552)**.

3.2.8 Application of Chiral–at–Cobalt Complexes.

Dimethylaminopyridine (DMAP) is an example of a nucleophilic catalyst that accelerates the rate of organic transformations *e.g.* esterification with anhydrides, the Baylis–Hillman reaction, hydrosilylations, Steglich rearrangement, Staudinger synthesis of beta–lactams *etc*. Ever since its initial discovery by the independent research groups of L. M. Litvinenko & A. I. Kirichenko [208] and W. Steglich & G. Hofle, [209] DMAP has been used as an effective acylation catalyst in the esterification of secondary alcohols with acid chlorides. For example, DMAP catalysed benzylation of *m*–chloroaniline is 10^4 x times faster compared to pyridine **(Scheme 126)**.
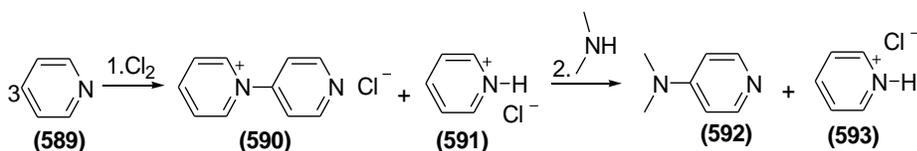
Scheme 126. Synthesis of DMAP in a two–step procedure from pyridine. [216–219]

Several chiral DMAP analogues have been developed for acyl transfer and applied to the kinetic resolution of secondary alcohols. The asymmetric nucleophile catalyses acyl transfer reactions, its mechanism is illustrated in **Figure 59.** Step 1, attack of chiral nucleophile on achiral acylating agent. The new chiral acylating agent reacts with a racemic mixture of alcohols. One enantiomer of that racemic source reacts faster with the asymmetric chiral acyl transfer reagent resulting in resolution. By using a stoiciometric quantity of achiral base the chiral nucleophile can be regenerated. The selectivity factor (*S*), relates to the ratio of the rate of a faster reacting enantiomer vs. the rate of the slower reacting enantiomer **(Figure 60)**.
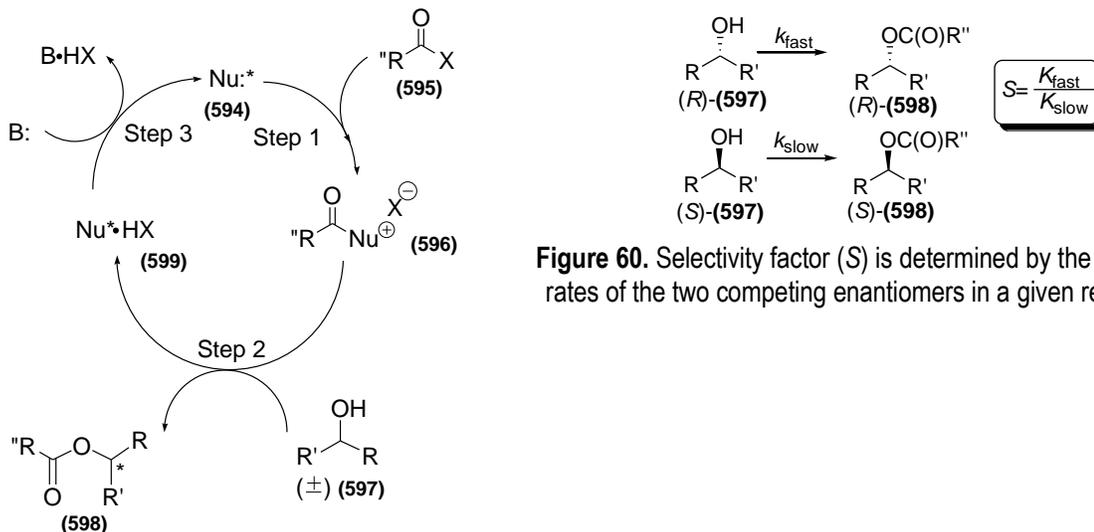
Figure 60. Selectivity factor (*S*) is determined by the reaction rates of the two competing enantiomers in a given reaction.

Figure 59. Catalytic cycle of a nucleophilic acyl transfer catalyst.

To explore applications of chiral–at–metal lactone complexes, (S_C,R_Co,P)*–**(567)** was synthesised. The crystal structure for this complex showed properties that could be potentially significant for asymmetric nucleophilic acyl transfer **(Figure 61)**. In general the vast majority of chiral DMAP catalysts contain a chiral group attached to position 3 (*i.e.* A). The challenge becomes for this to influence the environment of the active pyridine nitrogen as was demonstrated with **(297)** which is a imidazole **(Figure 21)**. [134] However, alternatively this problem can be solved by using a large group at position 3 to relay the stereochemical information contained within a chiral 4–amino substituent of B. The unique nature of chiral–at–metal complexes already discussed would be classed as A with the size of the complex significantly influencing the all important N of pyridine provided this environment is close to the chiral triphenylphosphine moiety **(Figure 62)**.
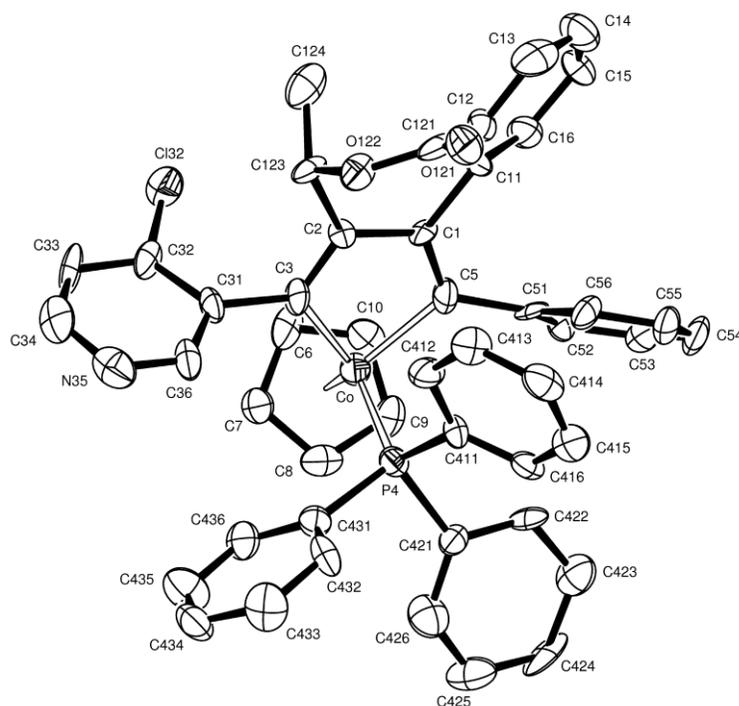
Figure 61. Molecular structure and atom numbering scheme for (S_C,R_{Co},P)*–**(567)** with 50% displacement ellipsoids, all H atoms are omitted for clarity. Selected bond distances (Å) and angles (°): C(1)–C(2) 1.421(10), C(2)–C(3) 1.345(11), C(1)–C(5) 1.330(11), Co–C(3) 1.986(8), Co–C(5) 1.985(8), Co–P(4) 2.200(2), C(5)–Co–P(4) 93.1(3), C(121)–O(122)–C(123) 123.7(7).
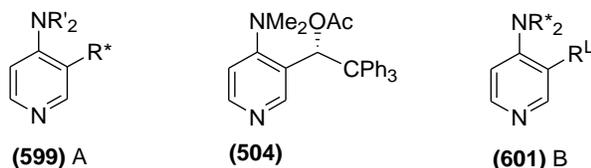
Figure 62. Application to the synthesis of a chiral 4–aminopyridine nucleophilic catalyst.

Reagent **(602)** was synthesised according to the literature report. [210] The ^{1}H and ^{13}C NMR data corresponded to the literature, [210] for example the ^{1}H NMR spectrum showed a characteristic singlet at δ 2.96 ppm which integrated for six protons, two mutually coupled doublets at δ 6.80 ppm and δ 8.31 ppm (*J* 5.7 Hz) a singlet at δ 8.76. This latter peak indicates the iodo atom is in the 3–position of the pyridine and three bonds away from the *N,N*–dimethylamine functionality **(Scheme 127)**. [210]
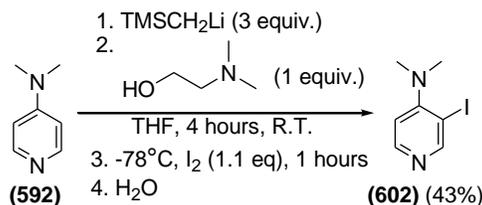
Scheme 127. Synthesis of 3–iodo–*N,N*–dimethylpyridin–4–amine **(602)**. [210]

3–Bromo–4–(pyrrolidin–1–yl)pyridine **(604)** was synthesised according to the literature procedure in a yield of 47%. The ^{1}H NMR spectrum showed a characteristic singlet at δ 8.34 ppm showing the bromine is in position 3 consistent with data in the literature **(Scheme 128)**. [211]
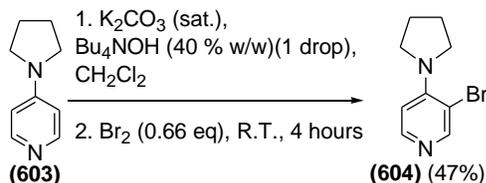
Scheme 128. Synthesis of 3–bromo–4–(pyrrolidin–1–yl)pyridine **(604)**. [211]

Attempts to synthesise previously reported [212]–[214] effective chiral DMAP or PPY derivatives **(607)** and **(608)** using **(605)** or **(606)** were unsuccessful. This was thought to be because the cross coupling was hampered by the electron rich and bulky nature of the amino group (dimethylamine and pyrrolidine) **(Scheme 129)**.
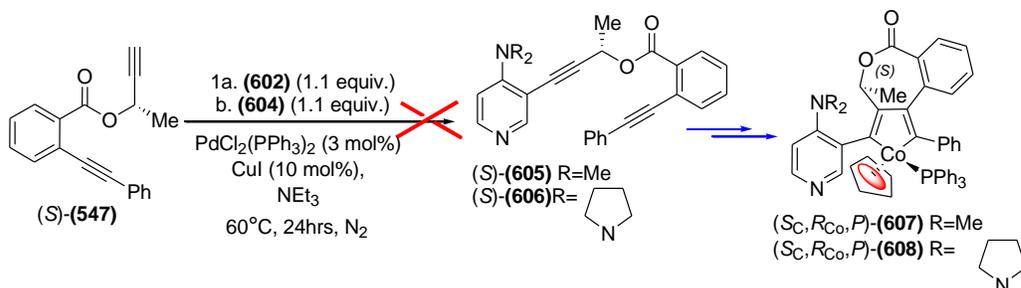
Scheme 129. Attempted synthesis of **(607)** and **(608)**.

3.3 Conclusions.

Ether– and ester–linked diynes were readily synthesised in two steps starting from secondary terminal propargylic alcohols. By using either a stoiciometric quantity of $(\eta^5–C_5H_5)(PPh_3)_2Co(I)$ **(368)** or 1.4 equiv. $CoCl(PPh_3)_3$ **(100)** and $Na(C_5H_5)$ **(486)** an important classes of achiral and chiral metallocyclopentadiene complexes were synthesised in reasonably good yields.

With respect to the lactone series a major isomer was formed as a result of relaying of chiral information from the chiral carbon to the metal centre which subsequently influenced the conformation of the phenyl groups on PPh_3. Locking of this conformation created a new defined sterocentre based around the coordinated phosphine.

The complexation that gave achiral and chiral–at–metal ether complexes appeared to be non selective with respect to the propeller chirality of the coordinated phosphine. Analytical HPLC (chiralcel OD column) was used to support epimerisation was not taking place at the metal although a dissociative pathway existed for this to occur at higher temperature.

This chapter also established that η^4–cyclobutadienes are probably not being formed as a consequence of the chiral diyne structure *i.e.* the carbon which has the central element of chirality also has an acidic proton which maybe promoting a decomposition pathway for both ether or lactone complexes. This also is a quandary as this central element of chirality is crucial to ensure diastereoselectivity in the configuration of the metal in both the ether and lactone series and at the phosphine in the case of the lactone complexes.

Chapter Four

DIASTEREOSELECTIVE SYNTHESIS OF PLANAR–CENTRALLY CHIRAL COBALT METALLOCENES.

4.0   Introduction to Insertion Reactions of Metallocyclopentadiene complexes.

This chapter of the thesis will discuss the preliminary results for the diastereoselective insertion reaction of isocyanides in organocobalt complexes to give novel planar chiral metallocenes.

H. Yamazaki and co workers were the first to report the isocyanide insertion reaction of *t*–butyl isocyanide **(609)** on achiral (η^5–cyclopentadienyl)(triphenylphosphine)–2,3,4,5–tetraphenylcobaltacyclopentadiene **(489a)** to give iminocyclopentadiene cobalt **(610)**. [215], [216] In 2000, I. Tomita and co workers re–visited the synthesis of **(610)** achieving an 88% yield after recrystallisation from benzene and hexane. [217]
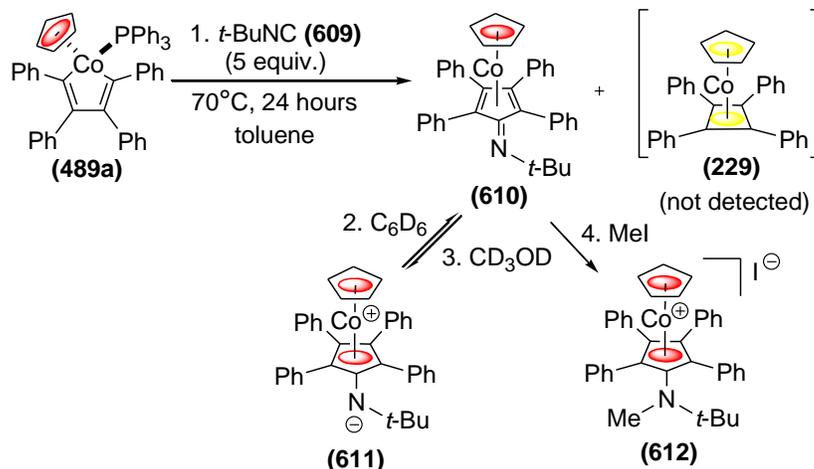
Scheme 130. Synthesis of iminocyclopentadiene–cobalt **(611)** and (η^4–tetra–phenylcyclobutadiene)(η^5–cyclopentadienyl) cobaltocenium iodide **(612)**. [217]

The reaction illustrated in **Scheme 130** was repeated as part of this project and found to be consistent with the literature reports. [215]–[217] Iminocyclopentadiene–cobalt **(610)** was synthesised in a clean reaction to give a 96% yield with no starting material or (η^4–tetra–phenylcyclobutadiene)(η^5–cyclopentadienyl)cobalt **(229)** metallocene.

Treatment of **(610)** with methyl iodide gave **(612)**. The physical properties of iminocyclopentadiene–cobalt **(610)** *i.e.* its fascinating solvachromatic behaviour was observed using spectroscopic techniques. The ^{1}H NMR spectrum showed an upfield shift of the *t*–butyl group of **(610)** in deuterated benzene *i.e.* from δ 1.28 ppm (9H, s, C(CH_3)$_3$) to δ1.00 ppm (9H, s, C(CH_3)$_3$) of **(611)** in deuterated methanol. Also a downfield shift of the η^5–cyclopentadienyl moiety which was initially at δ 4.68 ppm (5H, s, C$_5$H$_5$) in **(610)** to δ 5.41ppm (5H, s, C$_5$H$_5$) for **(611)** in deuterated methanol. A change in the colour was also readily visible. When dissolved in benzene a purple coloured solution was observed, but when treated with methanol a bright red colour was seen. IR spectroscopy showed the change in structure or zwitterionic character *i.e.* in the absence of a stretch at 1543 cm^{-1} (C=N stretch).

4.1   Diastereoselective Synthesis of Novel Planar Chiral Cobalt Metallocene.

The objective of this part was to determine if chiral–at–metal ether and or lactone systems allowed the insertion of isocyanides into carbon–metal bonds like their isoelectronic equivalent carbon monoxide. If so, the objective was to

determine the influence of the isocyanide and cobaltacyclopentadiene complex on the yield and diastereoselectivity of the insertion reaction.

Using metallocyclopentadiene ether complex $(S_C, R_{Co}, P/M)^*$– **(579)** (*d.r.*= 3:2) and applying reaction conditions used to make iminocyclopentadiene–cobalt **(610)**, *t*–butyl isocyanide did not undergo the insertion reaction after careful monitoring of the reaction. 2,6–Dimethylphenylisocyanide did however undergo the insertion reaction with an excellent yield and a reasonably good diastereomeric ratio of 2:1. The crude mixture which contained the (η^4–iminocyclopentadienyl)cobalt isomers appeared to be very difficult to purify by column chromatography requiring 1:1 of CH_3OH and CH_2Cl_2 and not distinguishing between the isomers. Therefore to help purify the diastereoisomers they were converted *in situ* during silica gel column chromatography purification to the (η^5–amino– cyclopentadienyl)cobalt metallocene using the strong acid HPF_6 (60% HPF_6 in water). Acid–hydrolysis enabled the *odiferous* excess of isocyanide reagent to be converted to their formamides. Though separation of the isomers could be achieved on a small scale by TLC, column chromatography failed to separate the isomers. Thus a filtration technique was developed which preserved the integrity of the diastereomeric ratio in the context of acquiring an accurate *d.r.* for the reaction and involved initially silica gel column chromatography using first hexane or 7:3 petroleum ether (40–60°C)/ethyl acetate to remove non polar impurities. Then to isolate both diastereoisomers 5% methanol, 15% methylene chloride, 2% HPF_6 (aqueous) and 78% hexane was used to elute both diastereoisomers. The mixture of solvents were removed under reduced pressure and dried in *vacuo.* The reaction mixture was then given an aqueous work up with methylene chloride /distilled water. This process was repeated 3 times to ensure the organic layer was clear. The organic layer was then dried with magnesium sulphate and filtered. The organic layer was evaporated to reveal a dark orange solid **(613)** (0.09 g, 97%, *d. r.*= 2:1).
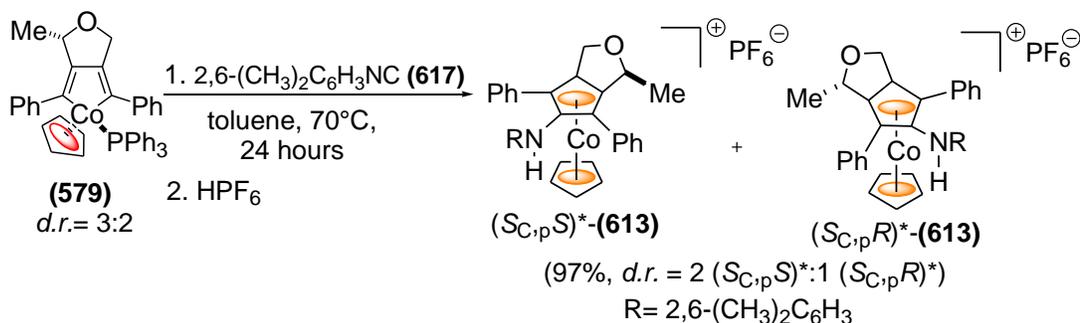
Scheme 131. Synthesis of planar chiral diastereoisomers of **(613)** using 2,6–dimethylphenylisocyanide.

Elemental analysis for the mixture of isomers was satisfactory. High resolution mass spectrometry gave a value of 516.1721 compared to calculated value of 516.1732 for the cation. The IR spectrum did not show a C=N stretch at *ca.* 1540 cm^{-1}. The ^{1}H NMR spectrum showed singlets at δ 5.34 (5H, s, $(S_C,_pS)^*$–C_5H_5) and δ 5.41 (5H, s, $(S_C,_pR)^*$–C_5H_5), which could also be seen in the ^{13}C NMR spectrum at δ 85.9 for $(S_C,_pR)^*$–C_5H_5 and δ 87.0 ppm for $(S_C,_pS)^*$–C_5H_5. The restricted rotation of the isomers was observed for the two methyl groups on the 2,6–positions which were non

equivalent δ 1.54 ppm (3H, s, $(S_{C,p}R)^*$–CH_3), δ 1.63 ppm (3H, s, $(S_{C,p}S)^*$–CH_3), δ 2.51 ppm (3H, s, $(S_{C,p}R)^*$–CH_3), δ 2.61 ppm (3H, s, $(S_{C,p}S)^*$–CH_3). The stereochemistry was assigned by comparison of the NMR data for the planar chiral metallocyclopentadienone complexes $(S_{C,p}S)^*$–**(347)** and $(S_{C,p}R)^*$–**(347)** which is structualy very similar.

The lactone complex $(S_C,R_{Co},P)^*$–**(552)** was treated with four equivalents of *t*–butyl isocyanide **(609)** and required heating to 70°C for three days in order for complete consumption of the starting material. Silica gel column chromatography resulted in **(614)** and it is thought to be formed as a result of methanol being used as one of elutants. To support the formulation of **(614)** the IR spectrum showed a stretch at 1461 cm^{-1} (C=N stretch). This compound was characterised further using ^{1}H and ^{13}C NMR as **(615)**. To support the structure an upfield signal at δ 0.71 ppm (a triplet) was observed that integrated for a three protons. The neighbouring protons showed geminal coupling and appeared as multiplets at δ 2.19 and 2.35 ppm integrating for one proton each. A singlet was observed at δ 3.79 ppm characteristically downfield and was assigned to OCH_3 group, at δ 0.85 ppm a singlet that integrated for nine protons (C(CH_3)$_3$) and a singlet at δ 5.79 ppm assigned to η–C_5H_5 was also observed. The ^{13}C NMR spectrum supported this assignment as correlation studies showed peaks at δ 27.7 ppm (CH_3), δ 28.7 ppm (CH_2) and δ 52.0 ppm (OCH_3) corresponding to ^{1}H NMR assignments. The diastereoselectivity could not be measured as the stereogenic marker was lost when the lactone ring opened **(Scheme 132)**.
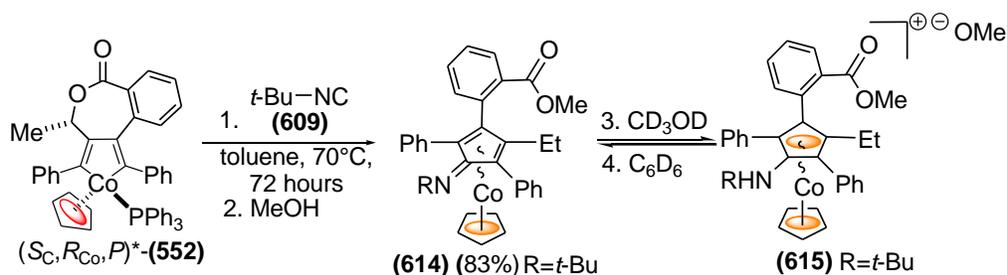
Scheme 132. Synthesis of **(614)** using *t*–butyl isocyanide **(609)**.

Using four equivalents of 2,6–dimethylphenylisocyanide, and heating at 70°C for 24 hours, gave **(616)** with a diastereomeric ratio of 2:1. Very polar solvent systems were explored *e.g.* 1:19, CH_3OH/CH_2Cl_2 for the separation of iminocyclopentadiene–cobalt isomers, but early and late fractions had the same ratio of isomers. Both iminocyclopentadiene–cobalt isomers were converted to (η^5–amino–cyclopentadienyl) cobalt isomers **(618)** using HCl. Silica gel column chromatography did not result in a separation of the isomers, hence, both isomers were characterised together. The mixture gave satisfactory elemental analysis. The ^{1}H NMR spectrum (δ, 400 MHz, CD_3OD) gave doublets at δ 0.87 ppm (3H, d, *J* 6.4 Hz, $(S_{C,p}S)^*$–CH_3) and at δ 1.12 ppm (3H, d, *J* 6.0 Hz, $(S_{C,p}S)^*$–CH_3). Two broad peak of unequal intensity was observed for the major isomer at δ 2.30 ppm (3H, brs, rotamers, $(S_{C,p}S)^*$–CH_3) and was thought to be as a result of restricted rotation of the C–Ar bond of **(618)**. Elevated temperature NMR revealed coalescence of the two rotamers.
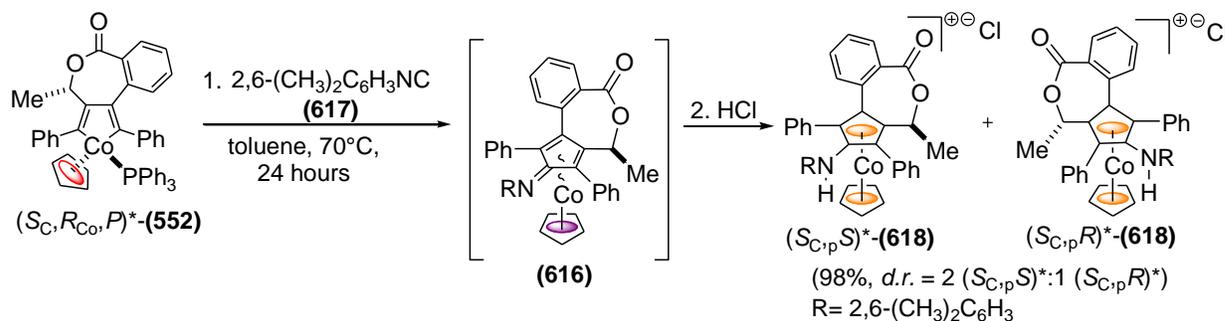
Scheme 133. Diastereoselective insertion reactions and synthesis of **(618)**.

Using (S_C,R_{Co},P)*–**(566)** only 50 mins with *tert*–butylisocyanide at 70°C was required for consumption of starting material. Silica gel column chromatography using acetic acid (glacial) caused the lactone to ring open and give a diastereomeric ratio of 4:3 of inseparable diastereoisomers of **(619) (Scheme 134)**. **Table 34** shows ^{1}H NMR data of key structural features for both major and minor diastereoisomers using deuterated methanol and benzene. The mixture gave a satisfactory elemental analysis and high resolution mass spectrometry (HRMS) showed $[M+H]^+$ = 668.1203.

Table 34. Spectroscopic comparison of diastereoisomers **(619)** with **(620).**

	major isomer $(S_C,_pR)$*–**(619)** and **(620)** δ_H ^{1}H NMR (δ, 400 MHz, ppm)		minor isomer $(S_C,_pS)$*–**(619)** and **(620)** δ_H ^{1}H NMR (δ, 400 MHz, ppm)	
	C_6D_6	CD_3OD	C_6D_6	CD_3OD
9H, s, C(CH_3)$_3$	δ 0.73	δ 1.00	δ 0.76	δ 1.03
3H, d, J 6.8 Hz, CH_3	δ 0.98	δ 0.97	δ 1.01	δ 0.96
3H, s, OCH_3	δ 3.32	δ 3.75	δ 3.29	δ 3.71
1H, q, J 6.8 Hz, CH	δ 4.30	δ 4.20	δ 4.19	δ 4.04
5H, s, C$_5H_5$	δ 5.61	δ 5.90	δ 5.62	δ 5.87
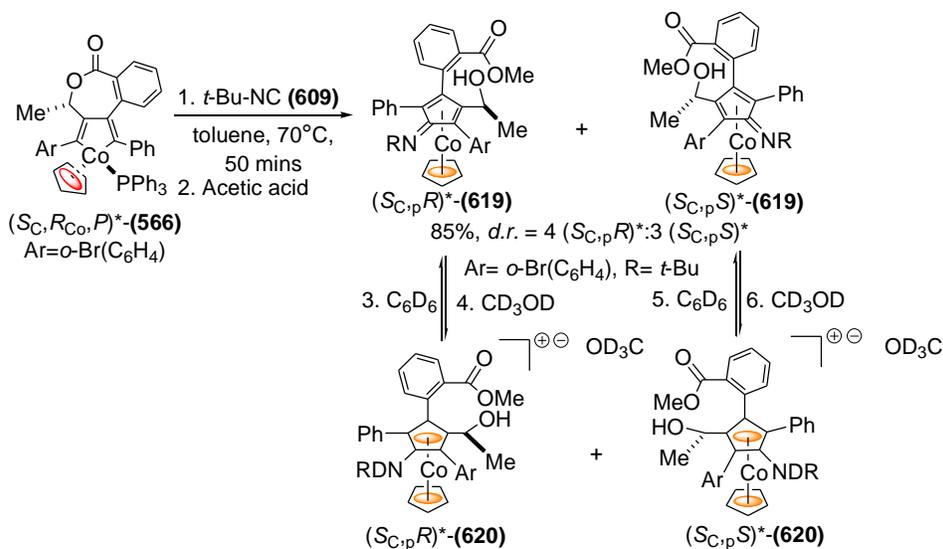
Scheme 134. Synthesis of ring opened planar chiral diastereoisomers **(619)** and **(620)**.

Using exactly the same reaction conditions used to make **(610)**, but changing the method of purification, allowed **(621)** to be obtained in 84% yield with a diastereomeric ratio of 4:3. To support identity of the metallocene and show the lactone was present the IR spectrum showed a carbonyl stretch at 1710 cm^{-1}. Moreover the major diastereoisomer showed a quartet and doublet from the intact chiral CHMe group *i.e.* δ 1.47 (3H, d, *J* 7.2 Hz, C*H*$_3$) and δ 4.54 ppm (1H, q, *J* 7.2 Hz, C*H*) **(Scheme 135)**.
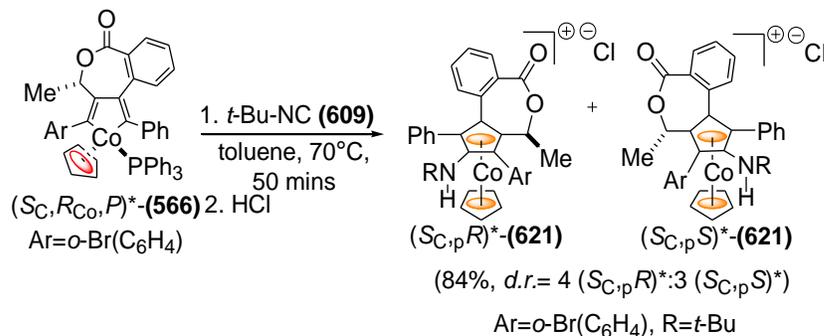
Scheme 135. Synthesis of ring opened planar chiral diastereoisomers of **(621)**.

Heating (*S*$_C$,*R*$_{Co}$,*P*)*–**(566)** with *tert*–butyl isocyanide **(609)** (4 equiv.) in toluene for 70 mins followed by the addition of methyl iodide and then filtering the solid precipitate gave diastereoisomers of **(622)** with a diastereomeric ratio of 3:1. An X–ray crystal structure of (*S*$_C$,$_P$*S*)*–**(622)** which is the minor isomer is illustrated in **Figure 63**. Surprisingly this new η^5–amino–cyclopentadienyl)cobalt complex showed the presence of an N–H bond rather than the expected N–Me bond. Thus it was thought this complex displayed a non–nucleophilic base character cleaving a hydrogen atom from an acidic molecule, possibly methyl iodide, but more likely from an aqueous contaminant. **Figure 64**, illustrates a proposed mechanism for isocyanide insertion.
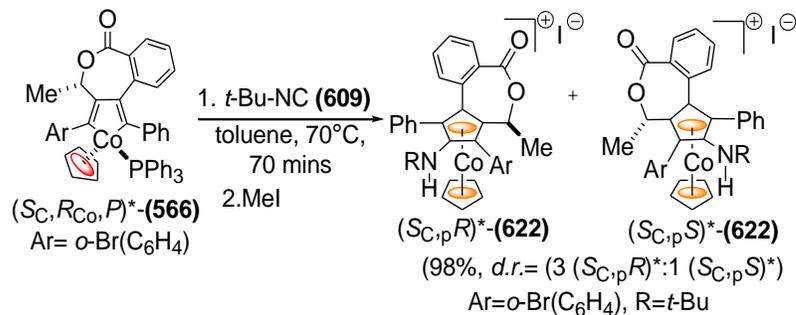
**Scheme 136.** Synthesis of planar chiral diastereoisomers of **(622)** using *tert*–butyl isocyanide **(609)**.
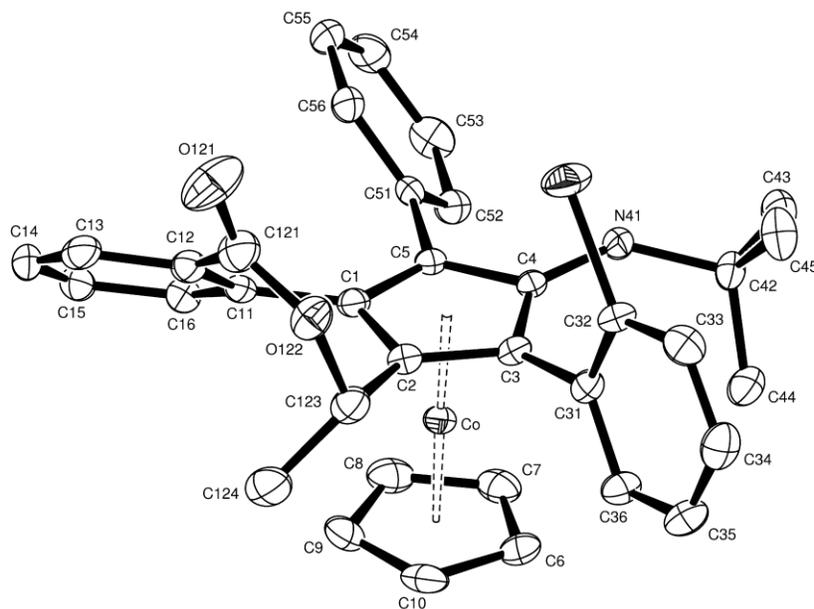
Figure 63. Molecular structure and atom numbering scheme for $(S_C,_pS)^*$–**(622)** with 50% displacement ellipsoids, all H atoms are omitted for clarity. Selected bond distances (Å) and angles (°): C(1)–C(2) 1.416(3), C(2)–C(3) 1.435(3), C(3)–C(4) 1.448(3), C(4)–C(5) 1.453(3), C(1)–C(5) 1.437(3), C(4)–N(41) 1.349(3), N(41)–C(42) 1.497(3), C(4)–N(41)–C(42) 134.03(19), C(121)–O(122)–C(123) 122.44(19).
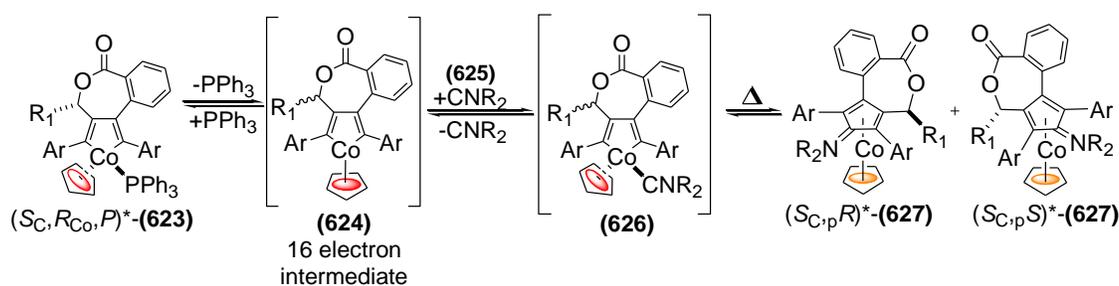
Figure 64. Mechanism of isocyanide insertion.

Using $(S_C,R_{Co},P)^*$–**(558)** and heating to 70°C using 4 equiv. of *tert*–butyl isocyanide **(609)** for 24 hours did not show any signs of the insertion reaction taking place from the analysis of TLC and crude ^{1}H NMR spectra. Elevating the

temperature and heating to reflux in a sealed tube only resulted in decomposition of the starting material. However, substituting the *tert*–butyl isocyanide **(609)** reagent with 2,6–dimethylphenylisocyanide **(617)** or 2–methyl–6–chlorophenylisocyanide **(632)** (4 equiv.) and heating at 70°C for 72 hours gave **(628)** in a diastereomeric ratio of 5:1 in 60% yield and **(629)** with a diastereomeric ratio of >5:1 in 65% yield **(Scheme 137)**. The assignments for the planar chiral metallocene were made by comparison of the NMR data available for ($S_{C,p}R$)*–**(350)** and ($S_{C,p}S$)*–**(350)**. A comparison can be made with the diastereoisomers of **(618) (Scheme 133)** *i.e.* substituting the methyl group with an *iso*–propyl group results in better diastereoselectivity from isocyanide insertion. Evidence that a diastereomeric ratio of 5:1 was present although complicated slightly by broadening of signals as a result of rotamers came from variable temperature (VT) NMR studies on **(628)**. By elevating the temperature in the NMR machine to 56°C rotamers of each planar chiral metallocene coalesced or lowering the temperature to –20°C showed broadening of each rotamer of major and minor planar chiral metallocenes (the ratio of rotamers can be found in the experimental, chapter 5). With respect to interconversion of species this phenomenon is thought to be possibly due to rotation of the aromatic between the N–CAr bond and thus its orientation is reflected in the NMR spectrum (model a). Another possibility is interconversion in the orientation of Cp–N (model b, *via* TS–1 and TS–2). This was difficult to establish as the proton of NH is acidic and may have been substituted with deuterium from CD$_3$OD. To support the formulation of the compounds and to determine the chirality of the major diastereoisomer a single crystal was used to obtain a X–ray crystal structure. **Figure 65** shows the relative stereochemistry of ($S_{C,p}R$)*–**(629)**. Both diastereomeric ratios and the outcome of the major diastereoisomer are consistent with and corroborate the results previously reported. [161] In comparison to the previously employed strategy this reaction is more effective as a better yield is obtained.
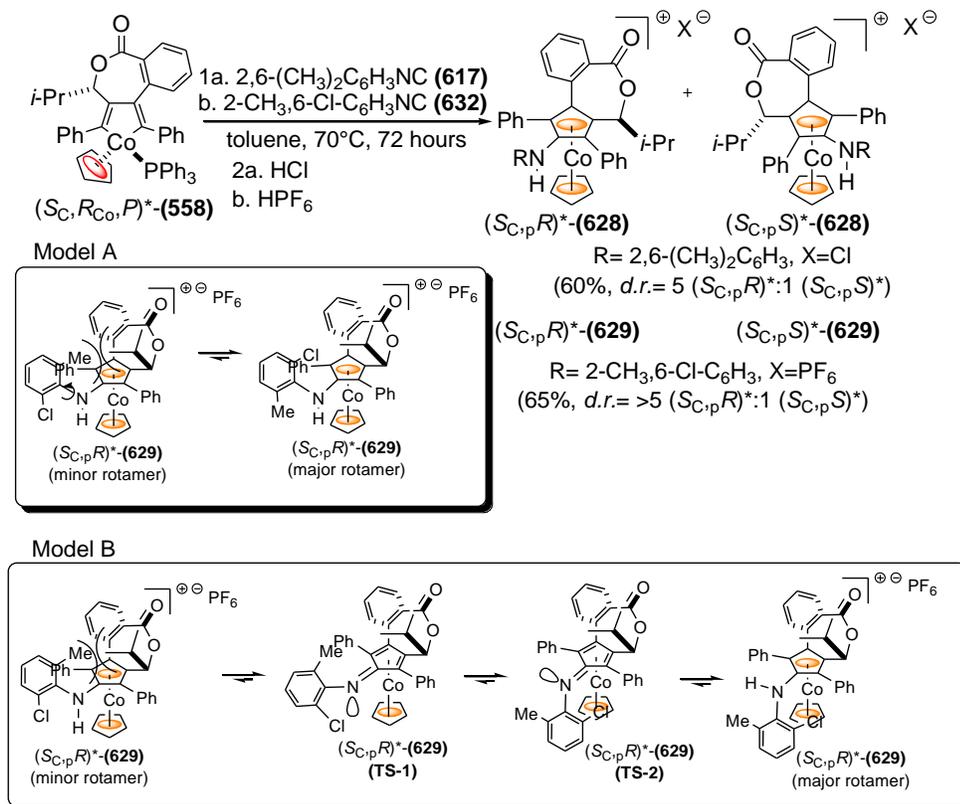
Scheme 137. Synthesis of planar chiral diastereoisomer **(628)** and **(629)**.
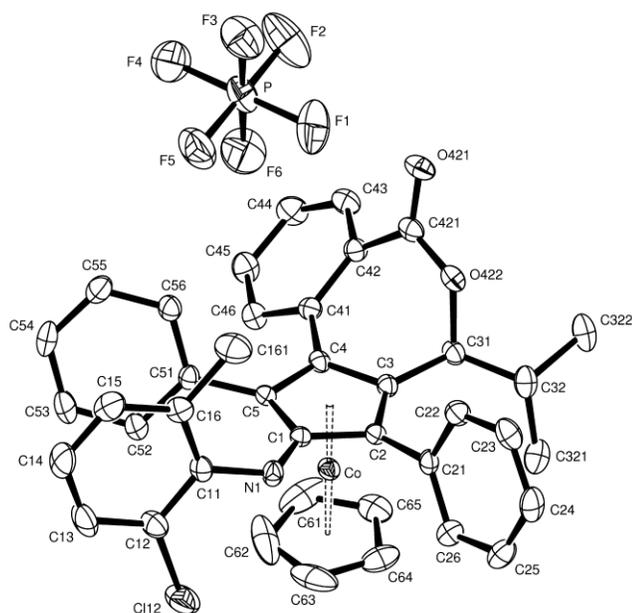
Figure 65. Molecular structure and atom numbering scheme for (S_C,$_p$$R$)*–**(629)** with 50% displacement ellipsoids, all H atoms are omitted for clarity. Selected bond distances (Å) and angles (°): C(1)–C(2) 1.443(2), C(2)–C(3) 1.433(3), C(3)–C(4) 1.434(3), C(4)–C(5) 1.434(3), C(1)–C(5) 1.442(3), C(1)–N(1) 1.343(2), N(1)–C(11) 1.429(2), C(1)–N(1)–C(11) 125.55(18), C(421)–O(422)–C(31) 121.08(15), C(321)–C(32)–C(322) 109.17(17).

Schemes 138, 139 show by using 2–methyl–6–cholrophenylisocyanide or 2,6–dimethylphenylisocyanide that the reagent does not affect the ratio of diastereoisomers. However, an important trend that is apparent from comparing the NMR data to the previously reported lactone where the central element of chirality has a methyl substituent is the minor planar chiral metallocyclopentadienone of (S_C,$_p$$S$)*–**(349)** appears to be the metallocene with the higher diastereomeric ratio as illustrated in both schemes. Enantiopure (S_C,R_{Co},P)–**(552)** as shown in **Scheme 140** gave a diastereomeric ratio of 2:1 similarly in favour of the (S_C,$_p$$S$) planar chiral metallocene in 92% yield.

Isocyanide derivatives that were also investigated included toluenesulfonylmethyl isocyanide (TOSMIC), 2–napthyl isocyanide and *n*–butyl isocyanide. Each reagent was added to either **(566)** or **(579).** However, no insertion process was detected or any planar chiral metallocenes.
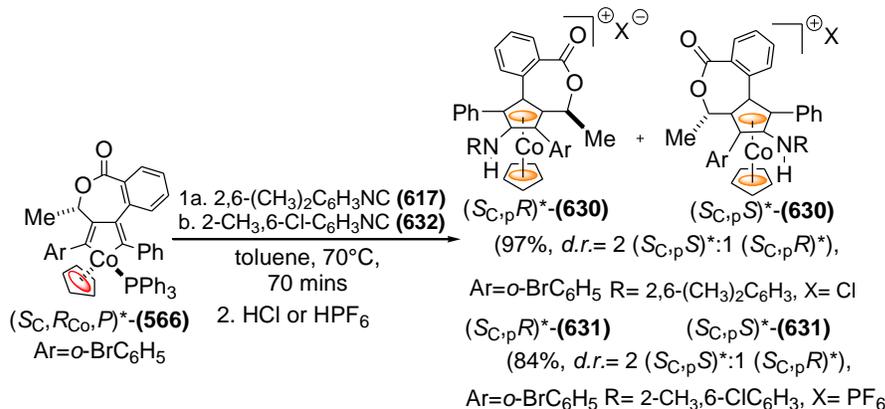
Scheme 138. Synthesis of planar chiral diastereoisomers **(630)** and **(631)**.
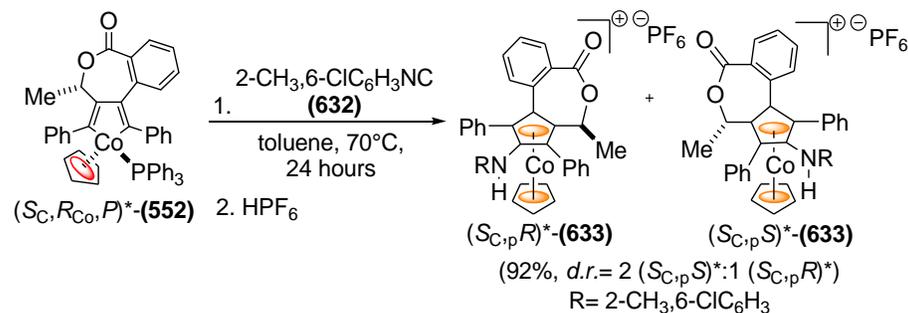
Scheme 139. Synthesis of planar chiral diastereoisomers **(633)**.
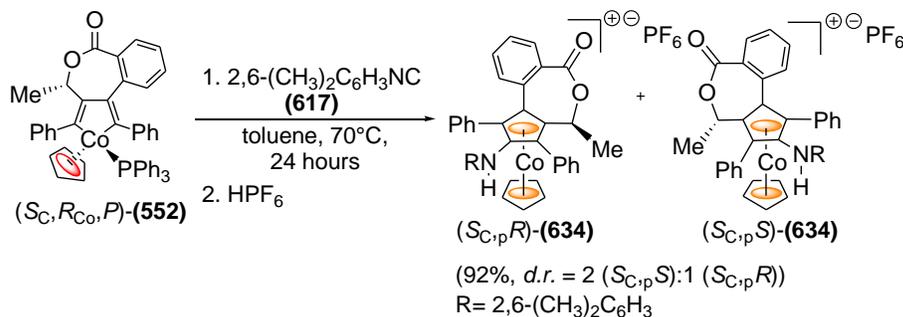
Scheme 140. Synthesis of planar chiral diastereoisomers **(634)** using enantiopure (S_C,R_{Co},P)–**(552)**.
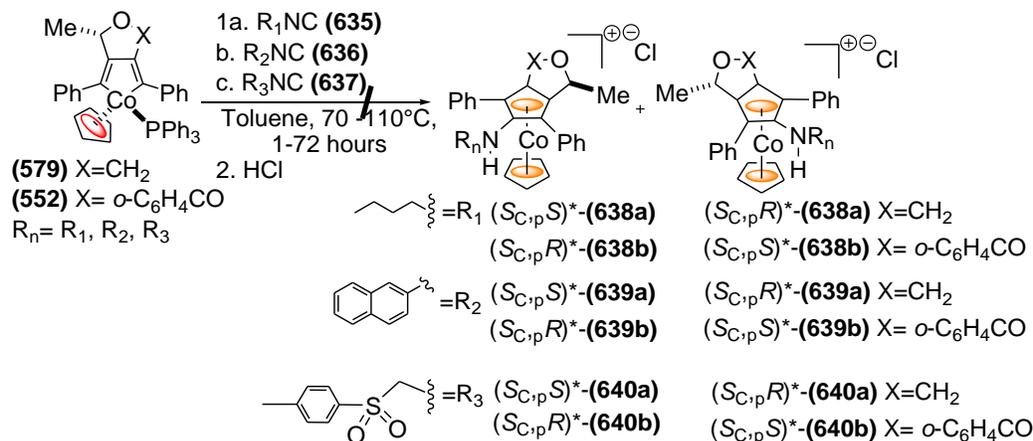
Scheme 141. Attempted synthesis of planar chiral diastereoisomers **(638)**–**(640)**.

4.2   Conclusions.

Chapter 4 has shown that several novel $(S_{C,p}R)^*,(S_{C,p}S)^*$–($\eta^5$–cyclopentadienyl)($\eta^5$–amino–cyclopentadienyl) cobaltacenium isocyanide compounds, including an enantiopure example, can be synthesised with ease in high yields and good diastereoselectivity of up to >5:1. However, the purification of these planar chiral diastereoisomers needs to be addressed. Although an effective method was developed for isolation of both diastereoisomers *i.e.* conversion to the amine salt, it significantly complicated spectroscopic analysis with respect to rotamers. But, the positive aspect of this method is that it is reversible by treatment with a suitable base like sodium hydroxide which reforms the imine diastereoisomers. If time permitted, other purification systems would have been explored as well as more conditions to increase the ratio for each planar chiral diastereoisomer.

4.3   Overall Conclusions

Several methods for the synthesis of chiral metallocyclopentadiene ether and lactone complexes have been investigated. In the case of the lactone series, a major diastereoisomer was observed by ^{1}H NMR, together with approximately three minor sets of signals. Recrystallisation allowed the structure to be determined by X–ray crystallography. Examination of the recrystallised material by ^{1}H NMR spectroscopy resulted in the same ratio of signals even after the spectrum was recorded at room temperature within several tens of seconds of preparation. Hence, no conclusion can be drawn on which isomer crystallised as if the NMR spectrum showed a thermodynamic mixture it is not possible to establish what the stereochemistry was prior to the crystal being dissolved. However, a strong case to support not involving epimerisation of the metal centered element of chirality due to phosphine dissociation was established with the configurationally stable at metal chiral ether metallocyclopentadiene complex.

With respect to isocyanide insertion reaction, as a result of the isocyanide moiety being significantly smaller than a triphenylphosphine or as previously observed with the isoelectronic equivalent carbon monoxide, it is therefore less discriminating on coordination, thus a lower diastereomeric ratio is observed.

Similarly in the case of the metallocyclopentadiene ether complexes, although the configurational chirality of a coordinated phosphine was compromised, this did not interfere with the chirality at metal during isocyanide insertion as the configuration at metal was stable enough to give the same opportunity for phosphine dissociation followed by isocyanide coordination and selective insertion based on the structural merits of the complex. Therefore, in summary it was established that a bulky functionality gave a better diastereomeric ratio and o–BrC$_6$H$_4$ substituted aromatic substituent adjacent to the metal required a much shorter reaction time.

4.4   Future Targeted Synthesis.

The reactions illustrated in **Scheme 142, 143** are proposed methods that can be used to synthesise novel planar chiral metallocenes.
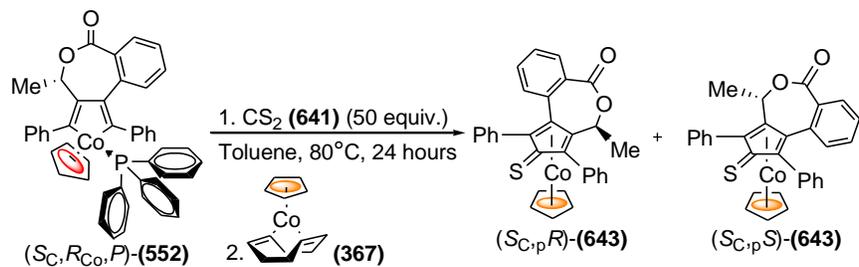
Scheme 142. Proposed method of synthesis of insertion reagents *via* in situ using CS$_2$ and η^5–C$_5$H$_5$Co(COD).
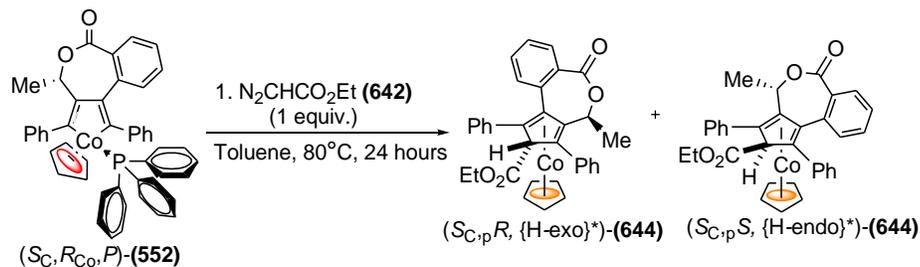
Scheme 143. Proposed method for the introduction of carbene moiety at the metal centre using ethyl diazoacetate.

Chapter Five

5.0   Experimental Procedures.

Air sensitive reactions were performed under an inert (nitrogen) atmosphere using a Schlenk line. Tetrahydrofuran and diethyl ether were distilled from sodium benzophenone ketyl. Dichloromethane and dimethylformamide were distilled from calcium hydride. Toluene was distilled from sodium wire. Petroleum ether refers to that fraction with a boiling range of 40–60°C. Column chromatography was performed using silica gel (Kieselgel Merck Typ9385 230–400 mesh, 40–63 μm). High performance liquid chromatography (analytical HPLC) was recorded using a ChiralCel OD–Cellulose *tris*(3,5–dimethylphenylcarbamate) coated on 10 μm silica–gel. Thin layer chromatography was performed with Keiselgel 60 F_{254} aluminium sheets. Several TLC dips were used which include; iodine, vanillin, ammonium molybdate, potassium permanganate and phosphomolybdic acid. Optical rotations were measured on Jasco P–1010 instrument or Perkin–Elmer model 241 polarimeter. All melting points were carried out using Griffin MFB–700–010U melting point apparatus (cooling plug 230V 50/60 Hz temperature ambient to 350°C). Minerlight Lamp UVGL–58 UV 254/365 nm was used to detect UV active spots. Microwave reactions were carried out using a CEM Discover instrument (300 W).

All reagents, solvents and starting materials were purchased from Sigma Aldrich, Tokyo Chemical Industries (TCI), Avocado, Appollo, Alfa Aesar, Lancaster, Fisher Scientific or Strem and used without purification unless otherwise stated. Butyllithium was purchased from Aldrich.

5.1   Characterisation.

Spectra were obtained using Joel JNM–EX 270 MHz in $CDCl_3$ solution unless otherwise stated for ^{1}H, 67 MHz for ^{13}C and 109 MHz for ^{31}P NMR or Bruker ultrashield 400 MHz for ^{1}H and 100 MHz for [13]C. Chemical shifts are reported relative to internal tetramethylsilane (δ 0.00 ppm) for ^{1}H and for ^{13}C NMR δ 77.0 ppm relative to $CDCl_3$ unless otherwise stated. [1]H spectra were acquired using a single pulse experiment, with a relaxation delay of 1 second, the number of spectral accumulations was 8, 16, 32 or 64 scans and the 90° pulse width was 14.5 μ seconds. [13]C spectra were acquired using a standard ^{1}H decoupled pulse sequence, with a relaxation delay of 1 second, the number of spectral accumulations was 1,024–10,000 scans and the pulse width was 12.5 μ seconds. We have observed some complex multiplet patterns, in the ^{1}H–NMR and ^{13}C spectra in some instances showed second order intensity perturbation no attempt has been made to simulate these and analysis is done as though 1st order.

High resolution mass spectra (HRMS) were acquired by either fast atom bombardment (FAB), chemical ionisation (CI) or electrospray ionisation (ESI) using MAT95 XP mass spectrometer by the EPSRC National Mass Spectrometry Service Centre at the University of Swansea.

FT infra–red spectra were recorded on a Shimadzu FTIR–8300 spectrometer operating at a resolution of 1 cm^{-1} in the 450–4000 cm^{-1} range either as a nujol mull or neat liquid (thin film) on a NaCl disc. Spectra are recorded with nitrogen purge in sample compartment.

All samples were in chloroform. All spectra, abs and CD, were recorded in 1 mm path length quartz cuvettes and all had chloroform baseline spectra subtracted. Absorption spectra were recorded using a Hitachi 2900 spectrometer. CD spectra were recorded using a JASCO J810 spectropolarimeter fitted with a 450 W xenon arc lamp.

Elemental Analysis was recorded at London Metropolitan University using Carlo Erba 1106 elemental analyser.

X–ray crystallography data were collected using Oxford Diffraction Xcalibur–3 CCD diffractometer equipped with Mo–Kα radiation and graphite monochromator. Data were processed using CrysAlis–CCD and RED programs or CAD–4 diffractometer and Mo–Kα radiation λ 0.71073 Å or 0.69020 Å, using ω–2Θ scan at 160 or 120 K (unit cell parameters in appendix). Structures solved by direct method using SHELXS–97 program, refined anisotropically (non–hydrogen atoms) by full–matrix least–squares on F using SHELXS–97 program. The H–atoms were calculated geometrically and refined with riding model. The program ORTEP–3, PLATON was used for drawing the molecules. WINGX–7 was used to prepare material for publication. David Hughes at the University of East Anglia and Majid Metovelli at Queen Mary University of London collected and processed all X–ray crystallography data.

5.2 Representative Formation of Cobalt–Complexed Propargyl Alcohols (Modified Procedure). [174]

$Co_2(CO)_8$ (1 equiv.) was transferred under nitrogen to a dry, preweighed round bottom flask (100 mL). Anhydrous CH_2Cl_2 (5 mL/mmol) was introduced *via* syringe followed by anhydrous CH_2Cl_2 (0.33 mL/mmol) solution of propargyl alcohol (1 equiv.). The solution was stirred for *ca.* 1.5–3.0 h until CO evolution was no longer visible. The solvent was removed by aspirator vacuum and the residue subjected to silica gel column chromatography. Elution, first with straight hexanes to remove cobalt derived impurities, followed by 20:1 hexane/EtOAc afforded protected propargylic alcohol or passed through a plug of neutral alumina using methylene chloride (10 mL/mmol) and used in subsequent reaction without further purification.

5.3 Representative Alkylation of Cobalt–Complexed Ether Bridged Diynes (Modified Procedure). [174]

Round bottom flask (100 mL) was charged with dicobalt hexacarbonyl propargyl alcohol (1 equiv.) and anhydrous CH_2Cl_2 (1 mL/mmol) and cooled to 0°C. $BF_3 \cdot OEt_2$ (4 equiv.) was added and left to stir at 0°C for *ca.* 20 mins before the appropriate nucleophile (2.5 equiv.) was syringed inside. The reaction mixture was allowed to gradually warm to room temperature. The reaction was quenched by the addition of saturated $NaHCO_3$ (1 mL/mmol) and a further 8 mL/mmol of CH_2Cl_2 was added and the organic solution washed with deionised water (10 mL/mmol) and saturated brine (10 mL/mmol), dried over $MgSO_4$ before being filtered. The solvent was removed by rotary evaporation. Silica gel column chromatography (hexanes, then 20:1 hexane/ethyl acetate unless specified) was used to purify the crude mixture. [Note: complexes needed to be stored below –20°C under an inert atmosphere otherwise decomposed].

5.4   Representative Procedure for Intramolecular Dynamic Kinetic Resolution.

Round bottom flask (250 mL) was charged with **(409b)** (1 equiv.), **(415)** (1 equiv.) and CH_2Cl_2 (1 mL/ mmol) and cooled to –35°C and left to stir for *ca.* 3 hours. Nucleophile (4 equiv.) was either (1a) syringed inside at –35°C and the reaction mixture allowed to warm up to room temperature or (1b) the reaction mixture was allowed to warm to room temperature and then the nucleophile (4 equiv.) was syringed inside. Reaction mixture worked up and purified as in **section 5.3**.

5.5   Representative Procedure for Intermolecular Dynamic Kinetic Resolution.

Round bottom flask (250 mL) was charged with tetrafluoroborate salt (1 equiv.), propargyl alcohol dicobalt hexacarbonyl (1 equiv.) and anhydrous CH_2Cl_2 (1 mL/mmol) and cooled to –35°C for 15 mins. The reaction mixture was allowed to gradually warm to room temperature. Reaction mixture worked up and purified as in **section 5.3**.

5.6   Representative Procedure for Sonogashira Cross Coupling (Modified Procedure). [161]

In a Schlenk tube (100 mL) covered with aluminium foil, ethers or esters (1 equiv.) were stirred in anhydrous triethylamine (10 mL/mmol) and to this solution was added CuI (10 mol%), $PdCl_2(PPh_3)_2$ (3 mol%) and warmed to 60°C before the addition of ArI (1 equiv., unless specified). Reaction mixture was stirred overnight under nitrogen before being quenched with aqueous NH_4Cl (3x10 mL/mmol) and extracted using CH_2Cl_2 (10 mL/mmol). The organic layer and washed with sat. brine (10 mL/mmol) dried with $MgSO_4$, filtered and solvent removed *in vacuo.*The products were purified using silica gel column chromatography.

5.7   Representative Procedure for the Synthesis of Metallocyclopentadienes Complexes.

Procedure A: An oven dried Schlenk tube (100 mL) is fitted with a stirring bar, rubber septa, and nitrogen inlet. The flask is flushed with nitrogen and charged with diphenylacetylene/ achiral/ *rac*–or enantiopure diynes (1 equiv.) and chloro*tris*(triphenylphosphine)cobalt(I) (1.4 equiv.), THF (1 mL/mmol), and **(i)**; sodium η^5–cyclopentadienide or **(ii)**; η^5–carbomethoxycyclopentadienyl sodium (1.4 equiv.). The reaction mixture was then heated to 66°C for exactly 30 mins, before the solvent was removed in *vacuo.* The reaction mixture was then given an aqueous work up using ethyl acetate (10mL/mmol) and filtered through a Büchner funnel which was silica imbedded under reduced pressure 20 mL/mmol of ethyl acetate. The organic material was concentrated and silica gel column chromatography was performed. [Note: carbomethoxycyclopentadienyl sodium was synthesised *in situ.*by reacting sodium cyclopentadienylide 2.0 M in anhydrous THF (1.14 equiv.) was added to dimethyl carbonate (3.45 equiv.) and the resulting mixture heated at reflux for 4 hours before being added to chloro*tris*(triphenylphosphine)cobalt(I) (1 equiv)].

Procedure B: A oven dried Schlenk tube (100 mL) is fitted with a stirring bar, rubber septa, and nitrogen inlet. The flask is flushed with nitrogen and charged with diphenylacetylene/achiral/*rac*–or enantiopure diynes (1 equiv.), (η^5–cyclopentadienyl)*bis*(triphenylphosphine)cobalt(I) (1 equiv.) and anhydrous THF (1 mL/mmol). The reaction mixture was then heated to 66°C for exactly 30 mins, before the solvent was removed in *vacuo.* The reaction mixture was concentrated and silica gel column chromatography was performed.

Procedure C: Same as above Procedure **(B)**, but reaction mixture is heated at 66°C for exactly 45 mins.

5.8   Representative Procedure for the Synthesis of Planar Chiral Metallocenes.

Schlenk tube (100 mL) equipped with a magnetic stirrer and under nitrogen atmosphere was charged with metallocyclopentadiene (1 equiv.), anhydrous toluene (1 mL/mmol), and isocyanide (4 equiv.). The reaction mixture was then heated to 70°C until a one spot–to–one spot conversion on TLC, and then the solvent and non volatiles were removed *in vacuo*. The reaction mixture was purified by silica gel column chromatography using hexanes or 7:3 petroleum ether (40–60°C)/EtOAc as the first elutant solvent mixture which removed triphenylphosphine. Then to isolate both planar chiral diastereoisomers 5% MeOH/15% CH_2Cl_2/2% HPF_6 (aqueous Brønsted acid) or HCl (37% v/v) and 78% hexane. The solvents were then removed using rotary evaporator before being given an aqueous work up using a 1:1 CH_2Cl_2/deionised water, this process was repeated until organic layer was clear. The organic layer was then dried with $MgSO_4$, filtered and concentrated.

$CoCl(PPh_3)_3$

$C_{54}H_{45}ClCoP_3$
Mol. Wt.: 881.2426

(100).

Compound chloro *tris*(triphenylphosphine)cobalt(I) **(100)** was prepared from cobalt chloride hexahydrate (4.80 g, 20.00 mmol) using the literature method [170] and gave **(100)** in 75% yield. The m.p. of the compound 135–139°C (dec) was in agreement with the literature.

$C_7H_5CoO_2$
Mol. Wt.: 180.0466

(106).
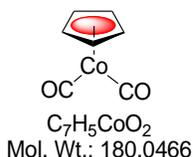
Compound (η^5–cyclopentadienyl)*bis*(carbonyl)cobalt(I) **(106)** was prepared from dicobalt octacarbonyl (2.50 g, 7.30 mmol) using a literature method [167] and gave **(106)** in 96% yield. The NMR data are in agreement with the literature and are given below for information.

(106): δ_H ^1H NMR (δ, 270 MHz, $CDCl_3$); 5.05 (3H, s, C_5H_5), 5.28 (2H, s, C_5H_5); δ_c ^{13}C NMR (δ, 67 MHz, $CDCl_3$); 53.5 (C_5H_5), 84.6 (CO).
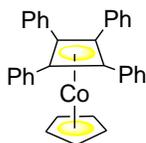
$C_{33}H_{25}Co$
Mol. Wt.: 480.4848

(229).

(1a); Compound (η^4–tetra–phenylcyclobutadiene)(η^5–cyclopentadienyl)cobalt **(229)** was prepared from chloro *tris*(triphenylphosphine)cobalt **(100)** (0.86 g, 0.98 mmol) using a literature method $^{(170)}$ and gave **(229)** in 83% yield. The NMR data are in agreement with the literature and are given below for information.

(1b); By refluxing the intermediate achiral– at– metal complex **(489a)** (0.10 g, 0.13 mmol) in toluene (1 mL) for exactly 5 hours and then removing the solvent under reduced pressure gave **(229)** (0.58 g, 95%) as a bright yellow solid after silica gel column chromatography using only petroleum ether (40–60°C).

(1c); Round bottom flask (100 mL) was charged with diphenylacetylene (0.38 g, 2.14 mmol), (η^5–cyclopentadienyl)(1,5–cyclooctadiene)cobalt(I) **(367)** (0.25 g, 1.07 mmol) and decalin (1.5 mL), the reaction mixture was heated to reflux in a seal tube for 24 hours. The crude reaction mixture was dried *in vacuo.*and then purified by silica gel column chromatography as above in **(1b)**.

(1d); Compound (η^4–tetra–phenylcyclobutadiene)(η^5–cyclopentadienyl)cobalt **(229)** was prepared from (η^5–cyclopentadienyl)*bis*(carbonyl)cobalt(I) **(106)** (0.2 mL, 1.13 mmol) using a literature method $^{(167)}$ and gave **(229)** in 46% yield after silica gel column chromatography as above in **(1b)**.

(229): δ_H ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 4.62 (5H, s, C$_5$*H*$_5$), 7.14–7.23 (12H, m, ArC*H*), 7.41–7.46 (8H, m, ArC*H*); δ_C ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 74.9 (Cb), 83.3 (*C*$_5$H$_5$), 126.2 (4x*C*Ar), 128.0 (8xAr*C*H), 128.9 (8xAr*C*H), 136.5 (4xAr*C*H).
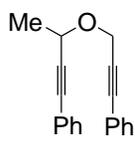
$C_{19}H_{16}O$
Mol. Wt.: 260.3297

Rac–**(343)**.

Compound *rac*–3–(4–phenylbut–3–yn–2–yloxy)prop–1–ynyl)benzene **(343)** was prepared from *rac*–(3–(prop–2–ynyloxy)but–1–ynyl)benzene **(502)** (1.76 g, 9.33 mmol) using the modified literature method $^{(161)}$ in **section 5.6** and gave *rac*–**(343)** in 97% yield. The NMR data are in agreement with the literature and are given below for information.

Rac–**(343)**: δ_H ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.61 (3H, d, *J* 6.7 Hz, C*H*$_3$), 4.51 (1H, d, *J* 15.6 Hz, C*H*$_2$), 4.66 (1H, d, *J* 15.6 Hz, C*H*$_2$), 4.72 (1H, q, *J* 6.7 Hz, C*H*), 7.07–7.72 (10H, m, ArC*H*); δ_C ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 22.3 (*C*H$_3$), 56.8

(CH_2), 64.8 (CH), 85.1 (CC), 86.0 (CC), 86.4 (CC), 88.4 (CC), 122.7 (CAr), 122.8 (CAr), 127.6 (2xArCH), 128.4 (2xArCH), 128.6 (ArCH), 130.4 (ArCH), 131.7 (2xArCH), 131.9 (ArCH), 132.0 (ArCH).

$C_{19}H_{16}O$
Mol. Wt.: 260.3297
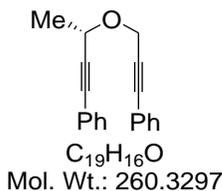
(*S*)–(–)–**(343)**.

Compound (*S*)–(–)–3–(4–phenylbut–3–yn–2–yloxy)prop–1–ynyl)benzene **(343)** was prepared from (*S*)–(–)–(3–(prop–2–ynyloxy)but–1–ynyl)benzene **(502)** (1.35 g, 7.33 mmol) using the modified literature method [161] in **section 5.6** and gave (*S*)–**(343)** in 99% yield.

(*S*)–**(343)**: $[\alpha]_D$ = –281.7 (*c* 0.014, 23.2°C, CHCl$_3$); ^{1}H NMR (δ, 400.0 MHz, CDCl$_3$); 1.60 (3H, d, *J* 6.7 Hz, CH_3), 4.50 (1H, d, *J* 15.6 Hz, CH_2), 4.65 (1H, d, *J* 15.6 Hz, CH_2), 4.71 (1H, q, *J* 6.7 Hz, CH), 7.07–7.72 (10H, m, 2xArCH); ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 22.4 (CH_3), 56.9 (CH_2), 64.9 (CH), 85.2 (CC), 85.9 (CC), 86.5 (CC), 88.5 (CC), 122.8 (CAr), 122.9 (CAr), 127.7 (2xArCH), 128.5 (2xArCH), 128.7 (ArCH), 130.5 (ArCH), 131.8 (2xArCH),132.0 (ArCH); +ve; HRMS; NESI; m/z, calculated for $C_{19}H_{20}O_2N$; [M+NH$_4$]$^+$; requires 278.1539, found 278.1540; HPLC (CHIRALCEL OD) 99.6:0.4 hexane/isopropyl alcohol, 1 mL/min R_t= 17 min 24 sec.

$C_{21}H_{20}O$
Mol. Wt.: 288.3829
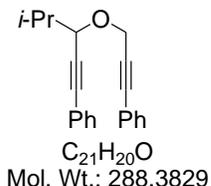
Rac–**(344)**.

Compound *rac*–(3–(4–methyl–1–phenylpent–1–yn–3–yloxy)prop–1–ynyl)benzene *rac*–**(344)** was prepared from (4–methyl–3–prop–2–ynyloxy–pent–1–ynyl)–benzene (1.60 g, 7.50 mmol) using the modified literature method [161] in **section 5.6** and gave *rac*–**(344)** in 95% yield. The NMR data are in agreement with the literature and are given below for information.

Rac–**(344)**: δ_H ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.13 (3H, d, *J* 6.8 Hz, CH_3), 1.15 (3H, d, *J* 6.8 Hz, CH_3), 2.12 (1H, *octet*, *J* 6.0 Hz, CH), 4.40 (1H, d, *J* 6.0 Hz, CH), 4.57 (1H, d, *J* 16.0 Hz, CH_2), 4.67 (1H, d, *J* 16.0 Hz, CH_2), 7.19–7.26 (6H, m, ArCH), 7.34–7.95 (4H, m, ArCH) ; δ_c ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 18.2 (CH_3), 19.0 (CH_3), 33.4 (CH_2), 57.1 (CH), 74.5 (CH), 85.5 (CC), 86.4 (CC), 86.7 (CC), 87.1 (CC), 123.0 (2xCAr), 127.7 (ArCH), 128.5 (2xArCH), 128.6 (ArCH), 128.7 (2xArCH), 131.8 (ArCH), 132.0 (2xArCH), 137.7 (ArCH).

C₂₅H₁₈O₂
Mol. Wt.: 350.4092
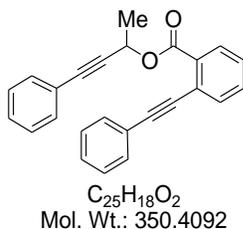
Rac–**(345)**.

Using the modified literature method [161] in **section 5.6** compound *rac*–4–phenylbut–3–yn–2–yl 2–(phenylethynyl)benzoate **(345)** was prepared from 4–phenylbut–3–yn–2–yl 2–iodobenzoate **(525)** (1.00 g, 2.65 mmol) to give *rac*–**(345)** in 99% yield. The NMR data are in agreement with the literature and are given below for information.

Rac–**(345)**: δ_H ¹H NMR (δ, 270 MHz, CDCl₃);1.64 (3H, d, *J* 6.7 Hz, C*H₃*), 5.91 (1H, q, *J* 6.7 Hz, C*H*), 7.15–7.23 (6H, m, ArC*H*), 7.30–7.35 (3H, m, ArC*H*), 7.41 (1H, td, *J* 7.4, 1.2 Hz, ArC*H*), 7.51–7.59 (3H, m, ArC*H*), 7.96 (1H, dd, *J* 7.9, 1.0 Hz, ArC*H*); δ_C ¹³C NMR (δ, 67 MHz, CDCl₃); 21.8 (*C*H₃) 61.8 (*C*H), 85.0 (*CC*), 87.7 (*CC*), 88.3 (*CC*), 94.7 (*CC*), 122.4 (*C*Ar), 123.4 (*C*Ar), 123.9 (*C*Ar), 128.0 (Ar*C*H), 128.3 (2xAr*C*H), 128.4 (2xAr*C*H), 128.6 (Ar*C*H), 128.7 (Ar*C*H), 130.8 (Ar*C*H), 131.8 (*C*Ar), 131.9 (3xAr*C*H), 132.0 (2xAr*C*H), 134.2 (Ar*C*H), 165.4 (*C*O).

C₂₅H₁₈O₂
Mol. Wt.: 350.4092
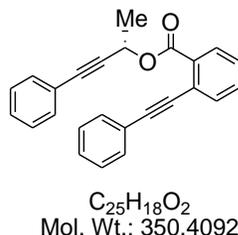
(*S*)–(–)–4–Phenylbut–3–yn–2–yl 2–(phenylethynyl)benzoate, **(345)**.

Compound (*S*)–(–)–**(345)** was prepared from (*S*)–(–)–but–3–yn–2–yl 2–(phenylethynyl)benzoate **(547)** (1.00 g, 5.68 mmol) using the modified literature method [161] in **section 5.6** to give (*S*)–(–)–**(345)** (1.99 g, quantitative).

(*S*)–**(345)**: $[\alpha]_D$ = –90.7 (*c* 1.20, 25.0°C, CHCl₃); ¹H NMR (δ, 400 MHz, CDCl₃); 1.60 (3H, d, *J* 6.4 Hz, C*H₃*), 5.88 (1H, q, *J* 6.4 Hz, C*H*), 7.11–7.18 (4H, m, ArC*H*), 7.22–7.27 (1H, td, *J* 7.4, 1.2 Hz, ArC*H*), 7.28–7.30 (3H, m, ArC*H*), 7.35 (1H, dd, *J* 7.2 Hz, ArC*H*), 7.47–7.53 (4H, m, ArC*H*), 7.93–7.90 (1H, d, *J* 8.0 Hz, ArC*H*); ¹³C NMR (δ, 100 MHz, CDCl₃); 22.0 (*C*H₃) 62.0 (*C*H), 85.2 (*CC*), 87.8 (*CC*), 88.5 (*CC*), 94.8 (*CC*), 122.5 (*C*Ar), 123.5 (*C*Ar), 124.1 (*C*Ar), 128.2 (Ar*C*H), 128.5 (2xAr*C*H), 128.6 (2xAr*C*H), 128.8 (Ar*C*H), 128.9 (Ar*C*H), 131.0 (Ar*C*H), 131.8 (*C*Ar), 132.0 (2xAr*C*H), 132.1 (Ar*C*H), 132.2 (2xAr*C*H), 134.4 (Ar*C*H), 165.5 (*C*O); +ve; HRMS; NESI; m/z, for C₂₅H₂₂O₂N; [M+NH₄]⁺; requires 368.1645, found 368.1647; HPLC (CHIRALCEL OD) 96.5:3.5 hexane/isopropyl alcohol, 1 mL/min R$_t$=9 min 6 secs (*S*–enantiomer), R$_t$= 7 min 24 secs (*R*–enantiomer).
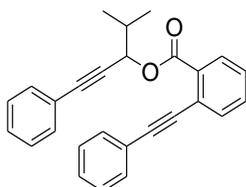
$C_{27}H_{22}O_2$
Mol. Wt.: 378.4624

Rac–**(346)**.

Using the modified literature method [161] in **section 5.6**, *rac*–4–methyl–1–phenylpent–1–yn–3–yl 2–(phenylethynyl)benzoate **(346)** was prepared from *rac*–4–methyl–1–phenylpent–1–yn–3–yl 2–iodobenzoate **(527)** (1.00 g, 2.48 mmol) to give *rac*–**(346)** in quantitative yield. The NMR data are in agreement with the literature and are given below for information.

Rac–**(346)**: δ_H ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.04 (3H, d, *J* 6.8 Hz, (C*H*$_3$)$_2$CH), 1.07 (3 H, d, *J* 6.8 Hz, (C*H*$_3$)$_2$CH), 2.16 (1H, *octet*, *J* 6.8 Hz, (CH$_3$)$_2$C*H*), 5.69 (1H, d, *J* 5.4 Hz, C*H*O), 7.17–7.20 (6H, m, ArC*H*), 7.30–7.33 (3H, m, ArC*H*), 7.39 (1H, m, ArC*H*), 7.50–7.52 (2H, m, ArC*H*), 7.56 (1H, d, *J* 7.6 Hz, ArC*H*), 7.94 (1H, d, *J* 7.6 Hz, ArC*H*); δ_C ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 18.0 ((CH$_3$)$_2$CH), 18.8 ((CH$_3$)$_2$CH), 33.0 (CH(CH$_3$)$_2$), 70.5 (*C*HO), 85.6 (*CC*), 86.4 (*CC*), 88.5 (*CC*), 94.9 (*CC*), 122.7 (*C*Ar), 123.6 (*C*Ar), 124.2 (*C*Ar), 128.1 (Ar*C*H), 128.5 (2xAr*C*H), 128.5 (2xAr*C*H), 128.7 (Ar*C*H), 128.7 (Ar*C*H), 130.9 (Ar*C*H), 131.9 (*C*Ar), 132.0 (2xAr*C*H), 132.1 (Ar*C*H), 132.2 (2xAr*C*H), 134.5 (Ar*C*H), 165.5 (*C*O).
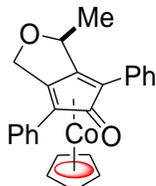
$C_{25}H_{21}CoO_2$
Mol. Wt.: 412.3662

(*S*,$_p$*S*)*–**(347)**.

Rac–**(394)** (0.25 g, 0.46 mmol), cyclopentadiene (0.06 mL, 0.92 mmol) was dissolved in toluene (2 mL) and heated at 110°C. The reaction mixture was then filtered through a short plug of silica gel, first with petroleum ether as eluent then 1:10 MeOHI/EtOAc. The solvent removed *in vacuo* and the ratio of diastereoisomers determined ^{1}H NMR this gave **(347)** (0.046 g, 24%, *d.r.*= 3:2). Using 1:19 MeOH/hexane gave a enriched (*S*,$_p$*S*)*–**(347)** (0.009 g, 5%) *d.r.*= 4:1. The compound is known in the literature [161] however synthesised using a novel method. The NMR data are in agreement with the literature and are given below for information.

(*S*,$_p$*S*)*–**(347)**: δ_H ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.36 (3H, d, *J* 6.7 Hz, C*H*$_3$), 4.58 (5H, s, C$_5$*H*$_5$), 4.86 (1 H, d, *J* 12.4 Hz, C*H*$_2$), 5.14 (1H, d, *J* 12.4 Hz, C*H*$_2$), 5.68 (1 H, q, *J* 6.7 Hz, C*H*), 7.36–7.39 (6 H, m, ArC*H*), 8.05 (2 H, d, *J* 8.2 Hz, ArC*H*), 8.17 (2 H, d, *J* 7.9 Hz, ArC*H*); δ_C ^{13}C NMR (δ,100 MHz, CDCl$_3$); 19.7 (*C*H$_3$), 67.1 (*C*HO), 72.5 (*C*Ph), 76.4 (*C*H$_2$O), 84.4 (*C*$_5$H$_5$), 91.7 (*C*Ar), 127.4 (Ar), 127.9 (Ar), 128.2 (Ar), 128.6 (Ar), 128.7 (Ar), 129.3 (Ar), 134.5 (Ar), 159.0 (*C*O).
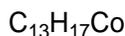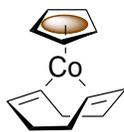
$C_{13}H_{17}Co$
Mol. Wt.: 232.2073

(367).

Compound (η⁵–cyclopentadienyl)(1,5–cyclooctadiene)cobalt(I) **(368)** was prepared from cobalt(III)acetylacetonate (5.09 g, 14.29 mmol) using the literature method [168] and gave **(368)** in 40% yield. The NMR data are in agreement with the literature and are given below for information.

(367): $δ_H$ ¹H NMR (δ, 270 MHz, CDCl₃); 1.59 (4H, m, 2xCH_2), 2.39 (4H, m, 2xCH_2), 3.47 (5H, s, C₅H_5), 4.58 (4H, s, 4xCH); $δ_c$ ¹³C NMR (δ, 67 MHz, CDCl₃); 32.1 (4xCH_2), 63.3 (4xCH), 83.8 (C₅H₅).
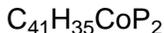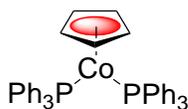
$C_{41}H_{35}CoP_2$
Mol. Wt.: 648.5973

(368).

Compound (η⁵–cyclopentadienyl)*bis*(triphenylphosphine)cobalt(I) **(368)** was prepared from chloro*tris*(triphenylphosphine)cobalt(I) **(100)** (15.00 g, 17.00 mmol) using two literature methods [170], [200] to give **(368)** in 68% yield. The yield appeared to be consistent with the literature of 53–69% (lit.).
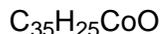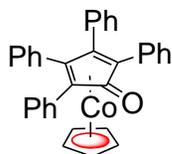
$C_{35}H_{25}CoO$
Mol. Wt.: 520.5056

(381).

Compound (η⁵–cyclopentadienyl)(tetraphenylcyclopentadienone)cobalt **(381)** was prepared from (η⁵–cyclopentadienyl)*bis*(carbonyl)cobalt(I) **(106)** (0.2 mL, 1.13 mmol) using a literature method [167] and gave **(381)** in 10% yield.

(381): IR (thin film) v_{max}; 1702, 1581 cm⁻¹; $δ_H$ ¹H NMR (δ, 270 MHz, CDCl₃); 4.63 (5H, s, C₅H_5), 7.21–7.22 (12H, m, ArCH), 7.44–7.46 (8H, m, ArCH).

Me
H
OH
(OC)$_3$Co········Co(CO)$_3$
C$_{10}$H$_6$Co$_2$O$_7$
Mol. Wt.: 356.0168
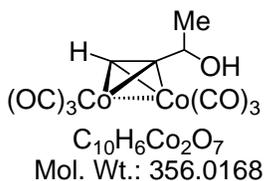
Rac–**(386)**.

Compound *rac*–but–3–yn–2–ol–3,4–dicobalt hexacarbonyl **(386)** is a known compound [229] and was prepared from *rac*–but–3–yn–2–ol **(104)** (0.50 g, 7.14 mmol) using the literature method [174] to give *rac*–**(386)** in 99% yield. The NMR data are in agreement with the literature and are given below for information.

Rac–**(386)**: IR (thin film) v$_{max}$; 3420 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.49 (3H, d, *J* 6.2 Hz, C*H*$_3$), 1.80 (1H, d, *J* 4.9 Hz, O*H*), 4.96 (1H, m, C*H*), 6.03 (1H, s, C*H*); δ$_c$ ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 25.7 (*C*H$_3$), 68.4 (*C*H), 71.4 (*C*C), 101.1 (*C*C), 199.6 (*C*O).

Me
OH
C$_{10}$H$_{10}$O
Mol. Wt.: 146.1858
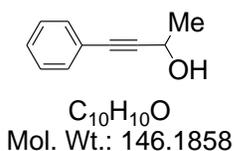
Rac–**(391)**.

Compound *rac*–4–phenyl–but–3–yn–2–ol **(391)** was prepared from phenylacetylene (3.00 mL, 27.00 mmol) using the literature method [161] and gave *rac*–**(391)** in 98% yield. The NMR data are in agreement with the literature and are given below for information.

Rac–**(391)**: δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.54 (3H, d, *J* 6.6 Hz, C*H*$_3$), 3.42 (1H, brs, O*H*), 4.76 (1H, q, *J* 6.6 Hz, C*H*), 7.25–7.27 (3H, m, ArC*H*), 7.39–7.50 (2H, m, ArC*H*); δ$_c$ ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 24.5 (*C*H$_3$), 58.9 (*C*H), 84.1 (*C*C), 91.1 (*C*C), 122.7 (*C*Ar), 128.4 (2xAr*C*H), 131.8 (2xAr*C*H), 132.2 (Ar*C*H).

Me
OH
C$_{10}$H$_{10}$O
Mol. Wt.: 146.1858

(*S*)–(–)–**(391)**.

(*S*)–(–)–*tert*–butyldiphenyl(4–phenylbut–3–yn–2–yloxy)silane **(587)** (1.00 g, 2.60 mmol) was charged with THF (10 mL) and cooled to 0°C. TBAF (2.88 mL, 2.88 mmol) was syringed inside and the reaction mixture was warmed to room temp. and stirred for 48 hours. The solvent was removed in *vacuo* and reaction mixture diluted with CH$_2$Cl$_2$ (80 mL) and poured into a separating funnel and given an aqueous work up with sat. NaHCO$_3$ (80 mL), sat. brine (80 mL) and the organic layer dried with MgSO$_4$. Silica gel column chromatography using 1:9 EtOAc/hexane gave (*S*)–(–)–4–phenylbut–3–yn–2–ol **(391)** as a colourless oil (0.40 g, quantitative). (*S*)–**(391)** is a known compound the NMR spectrum and optical rotation was found to be consistent with the literature and given below for information. [227]

(*S*)–(**391**): [α]$_D$ = –49.0 (*c* 1.0 , 26.7°C, dioxane); δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.52 (3H, d, *J* 6.8 Hz, C*H*$_3$), 1.81 (1H, s, O*H)*, 4.73 (1H, q, *J* 6.8 Hz, C*H*), 7.25–7.27 (3H, m, ArC*H*), 7.39–7.50 (2H, m, ArC*H*). δ$_c$ ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 24.6 (*C*H$_3$), 58.8 (*C*H), 84.0 (*C*C), 91.6 (*C*C), 123.0 (*C*Ar), 128.5 (2xAr*C*H), 128.9 (2xAr*C*H), 132.9 (Ar*C*H); HPLC (CHIRALCEL OD) 96.5:3.5 hexane/isopropyl alcohol, 1 mL/min R$_t$=53 min 6 sec.

C$_{16}$H$_{10}$Co$_2$O$_7$
Mol. Wt.: 432.1128
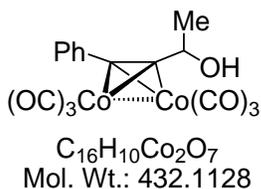
Rac–(**392**).

Compound *rac*–1–phenyl–but–3–yn–2–ol–3,4–dicobalt hexacarbonyl (**392**) is a known compound [228] and was prepared from 1–phenyl–but–3–yn–2–ol (**391**) (1.00 g, 6.83 mmol) using the literature method [174] to give *rac*–(**392**) in 95% yield. The NMR data are in agreement with the literature and are given below for information.

Rac–(**392**): IR (thin film) v$_{max}$; 3423, 1709 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.61 (3H, d, *J* 5.4 Hz, C*H*$_3$), 1.94 (1H, d, *J* 2.7 Hz, O*H*), 5.27 (1H, m, C*H*), 7.33–7.35 (3H, m, ArC*H*), 7.52–7.54 (2H, m, ArC*H*); δ$_c$ ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 25.3 (*C*H$_3$), 68.8 (*C*H), 90.8 (*C*C), 102.4 (*C*C), 128.1 (Ar*C*H), 129.1 (2xAr*C*H), 129.6 (2xAr*C*H), 137.2 (*C*Ar), 199.5 (*C*O).

C$_{19}$H$_{12}$Co$_2$O$_7$
Mol. Wt.: 470.1608
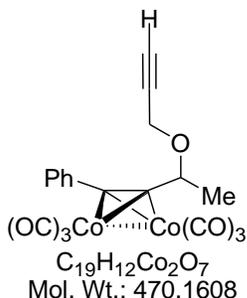
Rac–(**393**).

Using the general procedure in **section 5.3**, *rac*–(**392**) (0.40 g, 0.93 mmol) and propargyl alcohol (**396**) (0.13 mL, 2.33 mmol) gave *rac*–(**393**) (0.30 g, 68%) as a burgundy oil and (*S,S*)*–(**395**) (0.062 g, 15%) as a burgundy solid after purification using silica gel column chromatography with the elutant system 3:7 EtOAc/CH$_2$Cl$_2$ to obtain (**393**), 1:19 CH$_2$Cl$_2$/petroleum ether 40–60°C to get (*S,S*)*–(**395**).

Rac–(**393**): IR (thin film) v$_{max}$; 1612 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.59 (3H, d, *J* 6.2 Hz, C*H*$_3$), 2.46 (1H, t, *J* 2.7 Hz, C*H*), 4.34 (2H, dd, *J* 2.7 Hz, C*H*$_2$), 5.15 (1H, q, *J* 6.2 Hz, C*H*), 7.31–7.39 (3H, m, ArC*H*), 7.54–7.60 (2H, m, ArC*H*); δ$_c$ ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 22.1 (*C*H$_3$), 56.4 (*C*H$_2$), 74.4 (*C*H), 74.6 (*C*H), 79.9 (*C*C), 90.7 (*C*C), 99.2 (*C*C),

127.9 (ArCH), 128.9 (2xArCH), 129.7 (2xArCH), 137.9 (CAr), 199.5 (CO); +ve; LRMS; LSIMS; pFAB (NOBA); m/z, calculated for $C_{16}H_9Co_2O_6$; $[M-OCH_2C\equiv CH]^+ = 415.0$ (100).

$C_{25}H_{16}Co_2O_7$
Mol. Wt.: 546.2567
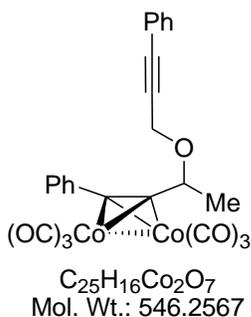
Rac–**(394)**.

Using the general procedure in **section 5.3**, *rac*–**(392)** (0.50 g, 1.12 mmol) and propargyl alcohol **(397)** (0.37 g, 2.80 mmol) gave *rac*–**(394)** (0.45 g, 71%) as a burgundy oil after purification using silica gel column chromatography with a 3:7 EtOAc/hexane.

Rac–**(394)**: IR (thin film) v_{max}; 3078, 1612 cm^{-1}; δ_H ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.62 (3H, d, J 5.9 Hz, CH_3) 4.51, (1H, d, J 16.0 Hz, CH_2), 4.54 (1H, d, J 16.0 Hz, CH_2), 5.21 (1H, q, J 5.9 Hz, CH), 7.25–7.38 (6H, m, ArCH), 7.40–7.49 (2H, m, ArCH), 7.53–7.63 (2H, m, ArCH); δ_c ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 22.2 (CH$_3$), 57.2 (CH$_2$), 74.4 (CH), 85.3 (CC), 86.5 (CC), 90.9 (CC), 99.4 (CC), 122.7 (CAr), 127.9 (ArCH), 128.4 (2xArCH), 128.6 (ArCH), 128.9 (2xArCH), 129.7 (2xArCH), 131.8 (2xArCH), 138.0 (CAr), 199.4 (CO); –ve; LRMS; pCI, (NH$_3$), m/z, calculated for $C_{25}H_{16}Co_2O_7$; $[M]^+ = 546.4$ (40).

$C_{35}H_{20}Co_4O_{13}$
Mol. Wt.: 884.2583
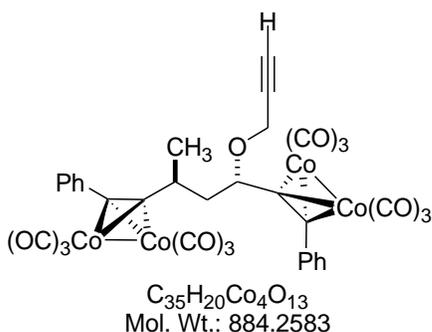
(*S,S*)*–**(395)**.

(*S,S*)*–**(395)**: m.p. 198–200°C; Anal. Calc. for $C_{35}H_{20}Co_4O_{13}$, Calc; C, 47.54; H, 2.28; Found; C, 47.53; H, 2.36; IR (thin film) v_{max}; 1575 cm^{-1}; δ_H ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.52 (3H, d, J 6.7 Hz, CH_3), 1.86 (1H, ddd, J 13.6, 1.7 Hz, CH_2), 2.29 (1H, ddd, J 13.6, 1.7 Hz, CH_2), 2.50 (1H, t, J 2.5 Hz, CH), 3.71 (1H, m, CH), 4.30 (1H, dd, J 16.3, 2.5 Hz, CH_2), 4.36 (1H, dd, J 16.3, 2.5 Hz, CH_2), 5.17 (1H, dd, J 16.3, 1.7 Hz , CH), 7.25–7.36 (6H, m, ArCH), 7.40–7.55 (4H, m, ArCH); δ_c ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 21.6 (CH$_3$), 33.7 (CH$_2$), 47.0 (CH), 57.5 (CH$_2$), 75.2 (CH), 75.5 (CC), 79.8 (CC), 91.6 (CC), 92.1 (CC), 96.9 (CC), 106.9 (CC), 127.7 (ArCH), 128.0 (ArCH), 128.8 (2xArCH), 129.0 (2xArCH), 129.4 (2xArCH), 129.5 (2xArCH), 137.7 (CAr), 138.2 (CAr), 199.2 (CO), 199.8 (CO); +ve; LRMS; LSIMS; pFAB (NOBA); m/z, calculated for $C_{35}H_{20}Co_4O_{13}Li$; $[M+Li]^+ = 889.9$ (30).
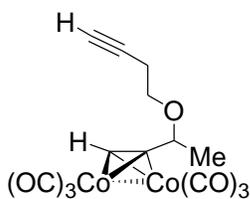
$C_{14}H_{10}Co_2O_7$
Mol. Wt.: 408.0914

Rac–**(400)**.

Using the general procedure in **section 5.3** *rac*–**(386)** (0.20 g, 0.56 mmol) and **(399)** (0.10 mL, 1.40 mmol) gave *rac*–**(400)** (0.21 g, 90%) as a burgundy oil after purification using silica gel column chromatography with a 3:7 EtOAc/hexane.

Rac–**(400)**: IR (thin film) ν$_{max}$; 1558 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.51 (3H, d, *J* 6.2 Hz, C*H*$_3$), 1.98 (1H, t, *J* 2.7 Hz, CC*H*), 2.48 (2H, td, *J* 7.2, 2.7 Hz, C*H*$_2$), 3.72 (2H, dq *J* 16.0, 7.2 Hz, C*H*$_2$), 4.62 (1H, q, *J* 6.2 Hz, C*H*), 6.09 (1H, s, C*H*); δ$_c$ ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 20.0 (*C*H$_3$), 23.3 (*C*H$_2$), 67.6 (*C*H), 69.4 (*C*H$_2$), 72.4 (*C*C), 75.8 (*C*C), 81.2 (*C*C), 97.2 (*C*C), 199.8 (*C*O); +ve; LRMS; LSIMS; pFAB (NOBA); m/z, calculated for $C_{10}H_5Co_2O_6$ [M–C$_4$H$_5$O]$^+$= 338.0 (70).
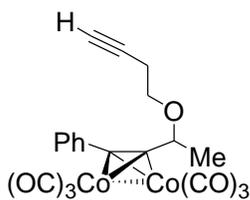
$C_{20}H_{14}Co_2O_7$
Mol. Wt.: 484.1874

Rac–**(401)**.

Using the general procedure in **section 5.3**, *rac*–**(392)** (1.22 g, 2.83 mmol) and **(399)** (0.5 mL, 11.32 mmol) gave *rac*–**(401)** as a burgundy solid (0.61 g, 44%) after purification using silica gel column chromatography with a 3:7 EtOAc/hexane.

Rac–**(401)**: IR (thin film) ν$_{max}$; 1705 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.55 (3H, d, *J* 6.2 Hz, C*H*$_3$), 1.96 (1H, t, *J* 3.4 Hz, C*H*), 2.49 (2H, td, *J* 7.2, 2.7 Hz, C*H*$_2$), 3.70 (2H, m, C*H*$_2$), 4.86 (1H, q, *J* 6.2 Hz, C*H*), 7.28–7.36 (3H, m, ArC*H*), 7.50–7.54 (2H, m, ArC*H*); δ$_c$ ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 20.1 (*C*H$_3$), 21.5 (*C*H$_2$), 67.6 (*C*H$_2$), 69.3 (*C*H), 76.2 (*C*H), 81.2 (*C*C), 90.5 (*C*C), 99.6 (*C*C), 127.7 (Ar*C*H), 128.8 (2xAr*C*H), 129.5 (2xAr*C*H), 137.9 (*C*Ar), 199.5 (*C*O); +ve; LRMS; LSIMS; pFAB (NOBA); m/z, calculated for $C_{18}H_{14}Co_2O_5$; [M–2CO]$^+$= 428.0 (100).
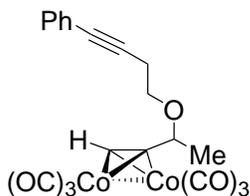
$C_{20}H_{14}Co_2O_7$
Mol. Wt.: 484.1874

Rac–**(402)**.

Using the general procedure in **section 5.6** *rac*–**(400)** (0.24 g, 0.60 mmol) and iodobenzene (0.06 mL, 0.56 mmol) gave *rac*–**(402)** (0.08 g, 31%) as a burgundy oil after purification using silica gel column chromatography with a 3:7 EtOAc/hexane.

Rac–**(402)**: IR (thin film) v_{max}; 1600 cm^{-1}; δ_H ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.52 (3H, d, *J* 6.2 Hz, C*H$_3$*), 2.70 (2H, t, *J* 7.2 Hz, C*H$_2$*), 3.69–3.89 (2H, m, C*H$_2$*), 4.63 (1H, q, *J* 6.2 Hz, C*H*), 6.09 (1H, s, C*H*), 7.25–7.28 (2H, m, ArC*H*), 7.36–7.40 (3H, m, ArC*H*); HRMS could not be obtained due to non homogeneity in the sample.
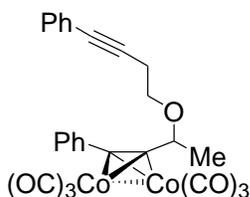
$C_{26}H_{18}Co_2O_7$
Mol. Wt.: 560.2833

Rac–**(403)**.

Using the general procedure in **section 5.6** *rac*–**(401)** (0.40 g, 0.93 mmol) and iodobenzene (0.11 mL, 1.02 mmol) gave *rac*–**(403)** as a burgundy oil (0.29 g, 56%) after purification using silica gel column chromatography with a 1:20 EtOAc/CH$_2$Cl$_2$.

Rac–**(403)**: IR (thin film) v_{max}; 1599 cm^{-1}; δ_H ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.57 (3H, d, *J* 6.2 Hz, C*H$_3$*), 2.71 (2H, t, *J* 6.9 Hz, C*H$_2$*), 3.80 (2H, m, C*H$_2$*), 4.90 (1H, q, *J* 6.2 Hz, C*H*), 7.26–7.31 (6H, m, ArC*H*), 7.32–7.38 (2H, m, ArC*H*), 7.51–7.55 (2H, m, ArC*H*); δ_c ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 15.4 (*C*H$_3$), 21.2 (*C*H$_2$), 22.4 (*C*H$_2$), 68.0 (*C*H), 81.6 (*C*C), 86.8 (*C*C), 90.7 (*C*C), 99.8 (*C*C), 123.8 (*C*Ar), 127.8 (2xAr*C*H), 128.3 (2xAr*C*H), 128.9 (2xAr*C*H), 129.7 (2xAr*C*H), 131.7 (2xAr*C*H), 138.0 (*C*Ar), 199.6 (*C*O); HRMS could not be obtained due to non homogeneity in the sample.
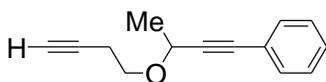
$C_{14}H_{14}O$
Mol. Wt.: 198.2604

Rac–but–3–ynyloxy but–1–ynyl benzene, **(404)**.

Compound *rac*–**(404)** was prepared by demetallation using the literature method [231], [232] and gave *rac*–**(404)** in 54% yield.

Rac–**(404)**: IR (thin film) v_{max}; 2985 cm^{-1}; δ_H ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.52 (3H, d, *J* 6.4 Hz, C*H*$_3$), 1.98 (1H, t, *J* 2.7 Hz, C*H*), 2.51 (2H, td, *J* 7.2, 2.7 Hz, C*H*$_2$), 3.61 (1H, dt, *J* 9.1, 7.2 Hz, C*H*$_2$), 3.90 (1H, dt, *J* 9.1, 7.2 Hz, C*H*$_2$), 4.44 (1H, q, *J* 6.4 Hz, C*H*), 7.25–7.32 (3H, m, ArC*H*), 7.40–7.45 (2H, m, ArC*H*); δ_C ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 22.0 (*C*H$_3$), 22.2 (*C*H$_2$), 66.0 (*C*H), 66.8 (*C*H$_2$), 69.4 (*C*H), 81.3 (*C*C), 85.2 (*C*C), 88.9 (*C*C), 122.8 (*C*Ar), 128.4 (3xAr*C*H), 131.7 (*C*Ar), 131.8 (Ar*C*H); +ve; HRMS; pCI; m/z, calculated for C$_{14}$H$_{18}$ON; [M+NH$_4$]$^+$; requires 216.1383, found 216.1381.
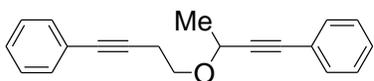
C$_{20}$H$_{18}$O
Mol. Wt.: 274.3563

Rac–4–(4–phenylbut–3–yn–2–yloxy)but–1–ynyl benzene, **(405)**.

(1a). Using the general procedure in **section 5.6** *rac*–**(404)** (0.30 g, 1.53 mmol) and iodobenzene (0.18 mL, 1.53 mmol) gave *rac*–**(405)** (0.13 g, 99%) as a colourless oil after silica gel column chromatography 1:20 EtOAc/hexane.

(1b). Compound *rac*–**(405)** was prepared by demetallation using the literature method [231], [232] and gave *rac*–**(405)** in 70% yield.

Rac–**(405)**: IR (thin film) v_{max}; 3078, 2978, 2866, 1599 and 1105 cm^{-1}; δ_H ^{1}H NMR (δ, 270 MHz, CDCl$_3$) 1.47 (3H, d, *J* 6.7 Hz, C*H*$_3$), 2.67 (2H, t, *J* 8.1 Hz, C*H*$_2$), 3.62 (1H, dt, *J* 8.1, 2.7 Hz, C*H*$_2$), 3.90 (1H, dt, *J* 8.1, 2.7 Hz, C*H*$_2$), 4.41 (1H, q, *J* 6.7 Hz, C*H*), 7.25–7.32 (6H, m, ArC*H*), 7.40–7.45 (4H, m, ArC*H*); δ_C ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 19.9 (*C*H$_3$), 21.2 (*C*H$_2$), 65.0 (*C*H), 66.1 (*C*H$_2$), 80.6 (*C*C), 84.1 (*C*C), 85.7 (*C*C), 88.0 (*C*C), 121.7 (*C*Ar), 122.7 (*C*Ar), 126.8 (2xAr*C*H), 127.2 (2xAr*C*H), 127.3 (Ar*C*H), 127.4 (Ar*C*H), 130.7 (2xAr*C*H), 130.8 (2xAr*C*H); +ve; HRMS; pCI; m/z, calculated for C$_{20}$H$_{22}$ON; [M+NH$_4$]$^+$; requires 292.1696, found 292.1697.
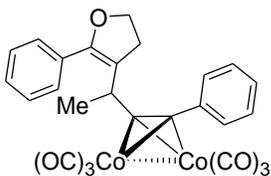
C$_{26}$H$_{18}$Co$_2$O$_7$
Mol. Wt.: 560.2833

Rac–4–(1–methyl–3–phenyl–prop–2–ynyl)–5–phenyl–2,3–dihydro–furan–3,4–dicobalt hexacarbonyl, **(407)**.

Using the general procedure in **section 5.3**, *rac*–**(392)** (1.00 g, 2.31 mmol) and propargyl alcohol **(406)** (0.84 mL, 5.77 mmol) gave *rac*–**(407)** as a burgundy solid (1.03 g, 79%) and (*S,S*)*–**(408)** (0.03 g, 3%) as a burgundy coloured solids after purification using silica gel column chromatography with a 3:7 EtOAc/hexane.

Rac–**(407)**: IR (thin film) v_{max}; 2974, 1601, 1481, 1447, 1242 cm^{-1}; ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.62 (3H, d, *J* 8.1 Hz, C*H*$_3$), 2.63 (1H, m, C*H*$_2$), 2.91 (1H, dt, *J* 10.8, 2.7 Hz, C*H*$_2$), 4.25 (1H, q, *J* 10.8 Hz, C*H*$_2$), 4.35 (1H, m, C*H*$_2$), 4.51 (1H, q, *J* 8.1 Hz, C*H*), 7.24–7.35 (6H, m, ArC*H*), 7.40–7.46 (4H, m, ArC*H*); δ$_c$ ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 22.4 (*C*H$_3$), 31.0 (*C*H$_2$), 36.8 (*C*H$_2$), 68.1 (*C*H), 92.3 (*C*≡C), 104.2 (*C*≡C), 112.7 (*C*=C), 127.6 (*C*=C), 127.7 (2xAr*C*H), 128.5 (2xAr*C*H), 128.7 (Ar*C*H), 128.8 (2xAr*C*H), 129.5 (2xAr*C*H), 131.6 (*C*Ar), 138.2 (Ar*C*H), 150.7 (*C*Ar), 199.7 (*C*O); +ve; LRMS; LSIMS; pFAB (NOBA); m/z, calculated for C$_{23}$H$_{18}$Co$_2$O$_4$; [M–3CO]$^+$= 476.1 (100).

C$_{42}$H$_{26}$Co$_4$O$_{13}$
Mol. Wt.: 974.3808
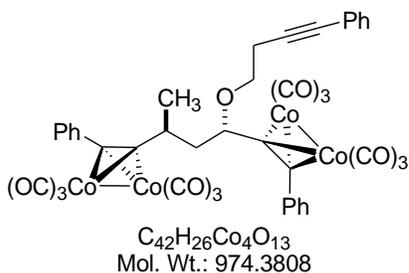
(*S,S*)*–**(408)**.

(*S,S*)*–**(408)**: m.p. 212–214°C; Anal. Calc. for C$_{42}$H$_{26}$Co$_4$O$_{13}$; Calc; C, 51.77: H, 2.69; Found: C, 51.72: H, 2.75; IR (thin film) v_{max}; 2928, 1605, 1481, 1443 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.50 (3H, d, *J* 6.4 Hz, C*H*$_3$), 1.85 (1H, ddd, *J* 12.1, 1.2 Hz, C*H*$_2$), 2.34 (1H, ddd, *J* 12.1, 1.2 Hz, C*H*$_2$), 2.72 (2H, m, C*H*$_2$), 3.75 (2H, m, C*H*$_2$), 4.00 (1H, m, C*H*), 4.96 (1H, dd, *J* 10.9,1.2 Hz, C*H*), 7.25–7.55 (15H, m, ArC*H*); δ$_c$ ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 21.6 (*C*H$_3$), 31.0 (*C*H$_2$), 34.0 (*C*H$_2$), 47.3 (*C*H), 69.7 (*C*H), 78.1 (*C*H$_2$), 81.6 (*C*C), 86.7 (*C*C), 91.6 (*C*C), 92.1 (*C*C), 97.9 (*C*C), 106.8 (*C*C), 123.6 (*C*Ar), 127.7 (Ar*C*H), 127.9 (2xAr*C*H), 128.3 (2xAr*C*H), 128.9 (4xAr*C*H), 129.4 (4xAr*C*H), 131.6 (2xAr*C*H), 137.8 (*C*Ar), 138.1 (*C*Ar), 199.3 (*C*O), 199.7 (*C*O).

C$_{16}$H$_9$BCo$_2$F$_4$O$_6$
Mol. Wt.: 501.9101
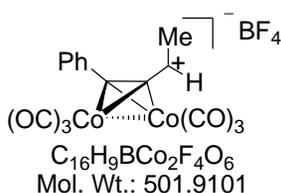
(409a).

Compound 1–phenyl–but–3–yn–2–ene tetrafluoroborate–3,4–(dicobalt hexacarbonyl) **(409a)** was prepared from *rac*–**(392)** (0.20 g, 0.45 mmol) using a literature method [230] and gave **(409a)** in 95% yield. The IR and ^{13}C NMR data is in agreement with the literature and are given below for information.

(409a): IR (thin film) v_{max}; 2964, 1491, 1369 cm^{-1}; δ$_C$ ^{13}C NMR (δ, 67 MHz, CD$_2$Cl$_2$); 22.7 (*C*H$_3$), 25.2 (*C*H), 68.6 (*C*C), 75.8 (*C*C), 128.8 (*C*Ar), 128.9 (3xAr*C*H), 129.7 (2xAr*C*H), 199.4 (*C*O).

$C_{16}H_8Co_2O_6$
Mol. Wt.: 414.0975
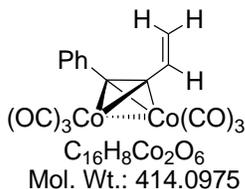
But–3–en–1–ynbenzene–3,4–dicobalt hexacarbonyl, **(415)**.

Enyne complex **(415)** is a known compound and mentioned in the literature as a by–product of **(409a)**. [174], [230], [232] The NMR data is in agreement with the literature and are given below for information.

(1a). A 100 mL flask was charged with **(409a)** (0.59 g, 1.16 mmol), 1,8–diazabicycloundec–7–ene (0.37 g, 2.40 mmol) and CH_2Cl_2 (12 mL) then stirred for 72 hours at room temperature. The reaction was poured into aqueous NH_4Cl (2x20 mL) and extracted CH_2Cl_2 (20 mL) and washed further with deionised water (20 mL) before being dried over $MgSO_4$. The solvent was removed by rotary evaporation. Silica gel column chromatography using 1:9 EtOAc/hexane or 1:19 EtOAc/CH_2Cl_2.gave **(415)** (0.41 g, 82%) as a burgundy solid.

(1b). Round bottom flask (100 mL) was charged with *rac*–**(392)** (0.50 g, 1.16 mmol), CH_2Cl_2 (15 mL) and few drops of trifluoroacetic acid (0.09 mL, 1.16 mmol) reaction mixture stirred overnight. Reaction mixture poured into deionised distilled water (20 mL) and organic layer extracted, dried over $MgSO_4$. Solvent removed on rotary evaporator to give **(415)** (0.22 g, 45%).

(415): δ_H ^{1}H NMR (δ, 270 MHz, $CDCl_3$); 5.57 (1H, d, *J* 10.1 Hz, C*H*), 5.71 (1H, d, *J* 16.6 Hz, C*H*), 7.07 (1H, dd, *J* 16.6, 10.1 Hz, C*H*), 7.28–7.36 (3H, m, ArC*H*), 7.51–7.53 (2H, m, ArC*H*); δ_c ^{13}C NMR (δ, 67 MHz, $CDCl_3$); 91.3 (*C*≡C), 92.4 (*C*≡C), 120.4 (*C*=C), 128.0 (*C*=C), 129.0 (2xAr*C*H), 129.3 (2xAr*C*H), 134.1 (Ar*C*H), 138.3 (*C*Ar), 199.1 (*C*O).

(*S,S*)*-**(418)** *anti*
$C_{34}H_{22}Co_4O_{13}$
Mol. Wt.: 874.2635

(*S,R*)*-**(418)** *syn*
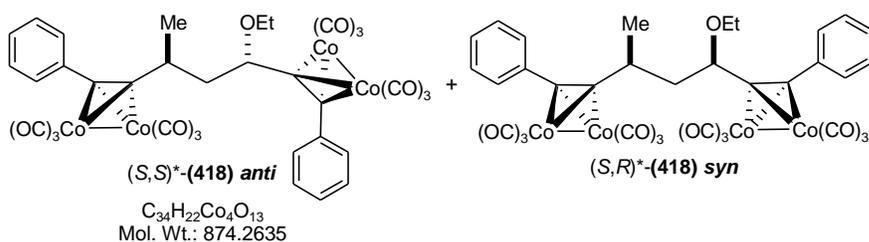
Schlenk tube (250 mL) was charged with *rac*–**(392)** (0.40 g, 0.93 mmol) dissolved in the minimum amount of Et_2O (1 mL) cooled to –35°C. HBF_4 (0.48 mL, 5.60 mmol) added and allowed to stir for 10 hours at –35°C until being warmed to room temp. The solvent was removed *in vacuo.* and purified by silica gel column chromatography (hexanes, then 20:1 hexane/EtOAc) to give **(418)** (0.05 g, 13%, *d.r.*= 15 (*S,S*)*:1 (*S,R*)*) and **(419)** (0.08 g, 17% yield) as burgundy solid.

(418): IR (thin film) v_{max}; 1605 cm^{–1}; δ_H ^{1}H NMR (δ, 270 MHz; $CDCl_3$) 1.24 (3H, t, *J* 6.9 Hz, C*H₃*), 1.50 (3H, d, *J* 6.7 Hz, (*S,S*)*–C*H₃*), 1.64 (3H, d, *J* 6.4 Hz, (*S,R*)*–C*H₃*), 1.82 (1H, ddd, *J* 13.1, 10.9, 2.0 Hz, C*H₂*), 2.28 (1H, ddd, *J* 13.1, 10.9,

2.0 Hz, C*H*$_2$), 3.60 (2H, q, *J* 6.9 Hz, C*H*$_2$), 3.86 (1H, *app* dq, *J* 6.7 Hz, C*H*), 4.80 (1H, dd, *J* 10.9, 2.0 Hz, C*H*), 7.28–7.34 (6H, m, ArC*H*), 7.38–7.47 (2H, m, ArC*H*), 7.54–7.58 (2H, m, ArC*H*); δ$_C$ ^{13}C NMR (δ, 67.0 MHz, CDCl$_3$); 15.3 (*C*H$_3$), 21.6 (2x*C*H$_2$), 34.1 (*C*H$_3$), 47.5 (*C*H), 67.1 (*C*H), 91.6 (*CC*), 91.8 (*CC*), 98.5 (*CC*), 106.9 (*CC*), 127.8 (2xAr*C*H), 128.9 (4xAr*C*H), 129.4 (2xAr*C*H), 129.5 (2xAr*C*H), 137.9 (*C*Ar), 138.2 (*C*Ar), 199.4 (*C*O), 199.8 (*C*O); +ve; HRMS; LSIMS; pFAB (NOBA); m/z, calculated for C$_{34}$H$_{20}$Co$_4$O$_{13}$; [M–2H]$^+$; requires 872.8900, found 872.9058.
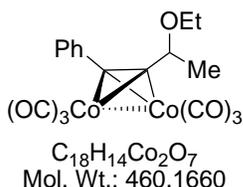
Rac–**(419)**.

Rac–**(419)**: δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$) 1.23 (3H, brs, C*H*$_3$), 1.53 (3H, brs, C*H*$_3$), 3.66 (2H, m, C*H*$_2$), 4.81 (1H, brs, C*H*), 7.28–7.36 (3H, m, ArC*H*), 7.51–7.53 (2H, m, ArC*H*); δ$_C$ ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 15.4 (*C*H$_3$), 22.6 (*C*H$_3$), 65.2 (*C*H$_2$), 75.7 (*C*H), 90.8 (*CC*), 100.5 (*CC*), 127.7 (Ar*C*H), 128.8 (2xAr*C*H), 129.7 (2xAr*C*H), 138.1 (*C*Ar), 199.9 (*C*O). HRMS could not be obtained due to non homogeneity in the sample.
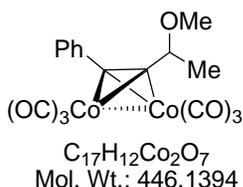
Rac–**(420)**.

Compound *rac*–**(420)** is a known compound and was prepared from *rac*–3–methoxy–but–1–ynyl benzene (0.10 g, 0.62 mmol) using the literature method [174] to give *rac*–**(420)** in 99% yield as a burgundy solid. The NMR data are in agreement with the literature and are given below for information.

Rac–**(420)**: IR (thin film) v$_{max}$; 2982, 2932, 1612, 1481, 1443 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.55 (3H, d, *J* 6.4 Hz, C*H*$_3$), 3.48 (3H, s, OC*H*$_3$), 4.71 (1H, q, *J* 6.4 Hz, C*H*), 7.28–7.36 (3H, m, ArC*H*), 7.51–7.53 (2H, m, ArC*H*); δ$_C$ ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 22.1 (*C*H$_3$), 57.5 (*C*H), 77.6 (O*C*H$_3$), 91.0 (*CC*), 99.7 (*CC*), 127.8 (Ar*C*H), 128.9 (2xAr*C*H), 129.7 (2xAr*C*H), 138.1 (*C*Ar), 199.6 (*C*O).
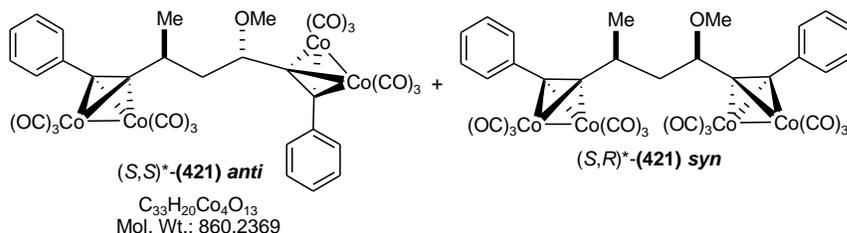
Using the general procedure **section 5.4**, **(1a) (415)** (0.50 g, 1.16 mmol), **(409b)** (0.58g, 1.16 mmol) and reagent grade CH_3OH (0.19 mL, 4.64 mmol) gave $(S,S)^*$–**(421)** (0.40 g, 40%, *d.r.*= 1:0) as a burgundy oil.

$(S,S)^*$–**(421)**: IR (thin film) v_{max}; 1605 cm^{-1}; δ_H ^{1}H NMR (δ, 270 MHz, $CDCl_3$); 1.49, (3H, d, *J* 6.7 Hz, CH_3), 1.84 (1H, ddd, *J* 13.6, 10.8, 2.0 Hz, CH_2), 2.32 (1H, ddd, *J* 13.6, 10.8, 2.0 Hz, CH_2), 3.55 (3H, brs, OCH_3), 3.63 (1H, m, CH), 4.75 (1H, dd, *J* 10.8, 2.0 Hz, CH), 7.25–7.34 (6H, m, ArCH), 7.41–7.54 (4H, m, ArCH) ; δ_C ^{13}C NMR (δ, 67.0 MHz, $CDCl_3$); 21.5 (CH_3), 34.0 (CH_2), 47.1 (CH), 59.4 (CH), 79.4 (OCH_3), 91.7 (CC), 92.0 (CC), 97.8 (CC), 106.8 (CC), 127.7 (ArCH), 127.8 (ArCH), 128.9 (4xArCH), 129.4 (4xArCH), 137.9 (CAr), 138.2 (CAr), 199.4 (CO), 199.8 (CO); +ve; LRMS; LSIMS; pFAB (NOBA); m/z, calculated for $C_{30}H_{20}Co_4O_{10}$; $[M–3CO]^+$= 776.0 (100).

Using the general procedure **section 5.4**, **(1b) (415)** (0.50 g, 1.16 mmol), **(409b)** (0.58g, 1.16 mmol) and reagent grade CH_3OH (0.19 mL, 4.64 mmol) gave **(421)** (0.19 g, 20%, *d.r.*= 2 $(S,S)^*$:3 $(S,R)^*$) and (E)–**(424)** (0.46 g, 48%) as burgundy coloured oils.

(421): δ_H ^{1}H NMR (δ, 270 MHz, $CDCl_3$); 1.49, (3H, d, *J* 6.7 Hz, $(S,S)^*$–CH_3), 1.54, (3H, d, *J* 6.2 Hz, $(S,R)^*$–CH_3), 1.84 (1H, ddd (*app* t), *J* 13.6, CH_2), 2.32 (1H, ddd (*app* t), *J* 13.6, CH_2), 3.48 (3H, brs, $(S,R)^*$–OCH_3), 3.55 (3H, brs, $(S,S)^*$–OCH_3), 3.63 (1H, m, $(S,S)^*$–CH), 3.71 (1H, m, $(S,R)^*$–CH), 4.75 (1H, m, $(S,S)^*$–CH), 4.77 (1H, m, $(S,R)^*$–CH), 7.25–7.34 (6H, m, ArCH), 7.41–7.54 (4H, m, ArCH).
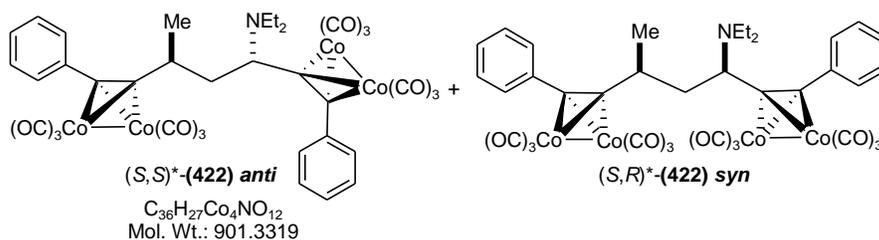
$(S,S)^*$-**(422)** *anti*
$C_{36}H_{27}Co_4NO_{12}$
Mol. Wt.: 901.3319

$(S,R)^*$-**(422)** *syn*

Using the general procedure **section 5.4 (1a)**, **(415)** (0.50 g, 1.16 mmol), **(409b)** (0.58 g, 1.16 mmol) and reagent grade $HNEt_2$ (0.48 mL, 4.64 mmol) gave $(S,S)^*$–**(422)** (0.39 g, 37%, *d.r.*= 1:0) as a burgundy oil.

$(S,S)^*$–**(422)**: IR (thin film) v_{max}; 1606 cm^{-1}; δ_H ^{1}H NMR (δ, 270 MHz, $CDCl_3$); 1.07 (6H, t, *J* 6.9 Hz, 2xCH_3), 1.41 (3H, d, *J* 6.4 Hz, CH_3), 1.80 (1H, ddd (*app* t), *J* 11.9 Hz, CH), 2.40 (1H, ddd (*app* t), *J* 11.9 Hz, CH), 2.56 (2H, dq, *J* 6.9 Hz, CH_2), 2.74 (2H, dq, *J* 6.9 Hz, CH_2), 3.63 (1H, brs, CH), 4.51 (1H, dd, *J* 11.9, 2.0 Hz, CH), 7.25–7.33 (6H, m, ArCH), 7.41–7.47 (4H, m, ArCH); δ_C ^{13}C NMR (δ, 67 MHz, $CDCl_3$); 15.6 (2xCH_3), 21.2 (CH_3), 34.7 (CH), 44.5 (3xCH_2), 60.7 (CH), 92.5 (CC), 95.3 (CC), 97.7 (CC), 107.8 (CC), 127.5 (ArCH), 127.6 (ArCH), 128.8 (2xArCH), 128.9 (2xArCH), 129.2 (2xArCH), 129.3 (2xArCH), 138.4 (CAr), 138.5 (CAr), 199.9 (2xCO); +ve; LRMS; LSIMS; pFAB (NOBA); m/z, calculated for $C_{34}H_{27}Co_4O_{10}N$; $[M–2CO]^+$= 845.0 (100), $[M–3CO]^+$= 816.9 (100).

Using the general procedure **section 5.4 (1b)**, **(415)** (0.50 g, 1.16 mmol), **(409b)** (0.58 g, 1.16 mmol) and reagent grade HNEt$_2$ (0.48 mL, 4.64 mmol) gave **(422)** (0.21 g, 20%, *d.r.*= 4 (*S,S*)*:3 (*S,R*)*), (*E*)–**(424)** (0.41 g, 43%) and **(423)** (0.30 g, 30%, *d.r.*= 4 (*S,S*)*:1 (*S,R*)*) as burgundy coloured oils.

(422): δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.07 (6H, t, *J* 6.9 Hz, 2xC*H*$_3$), 1.22 (4H, m, (*S,R*)*–2xC*H*$_2$), 1.41 (3H, d, *J* 6.4 Hz, (*S,S*)*–C*H*$_3$), 1.53 (3H, d, *J* 6.4 Hz, (*S,R*)*–C*H*$_3$), 1.80 (1H, ddd (*app* t), *J* 11.9 Hz, C*H*), 2.40 (1H, ddd (*app* t), *J* 11.9 Hz, C*H*), 2.56 (2H, dq, *J* 6.9 Hz, (*S,S*)*–C*H*$_2$), 2.74 (2H, dq, *J* 6.9 Hz, (*S,S*)*–C*H*$_2$), 3.63 (1H, brs, (*S,S*)*–C*H*), 3.65 (1H, brs, (*S,R*)*–C*H*), 4.51 (1H, dd, *J* 11.9, 2.0 Hz, (*S,S*)*–C*H*), 4.80 (1H, m, (*S,R*)*–C*H*), 7.25–7.33 (6H, m, ArC*H*), 7.41–7.47 (4H, m, ArC*H*).

(*S,S*)*-**(423)** *anti*
C$_{32}$H$_{18}$Co$_4$O$_{13}$
Mol. Wt.: 846.2103

(*S,R*)*-**(423)** *syn*
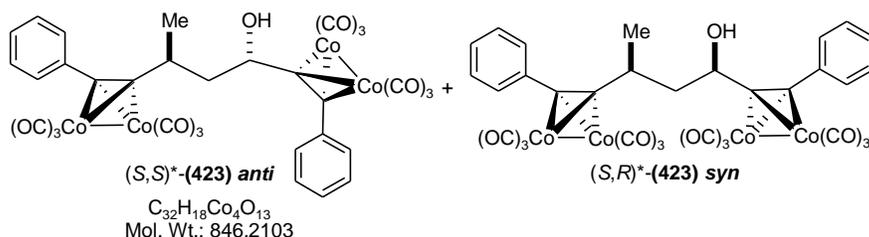
(423): IR (thin film) ν$_{max}$; 1706 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$) 1.51, (3H, d, *J* 6.7 Hz, (*S,S*)*–C*H*$_3$), 1.52, (3H, brs, (*S,R*)*–C*H*$_3$), 1.92 (1H, ddd, *J* 16.1, 13.6, 2.0 Hz, C*H*$_2$), 1.98 (1H, d, *J* 5.0 Hz, O*H*), 2.20 (1H, ddd, *J* 16.1, 13.6, 2.0 Hz, C*H*$_2$), 3.70 (1H, m, (*S,R*)*–C*H*), 3.75 (1H, m, (*S,S*)*–C*H*), 5.05 (1H, m, (*S,R*)*–C*H*), 5.23 (1H, ddd, *J* 7.2, 5.0, 2.0 Hz, (*S,S*)*–C*H*), 7.25–7.34 (6H, m, ArC*H*), 7.41–7.54 (4H, m, ArC*H*); δ$_C$ ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 21.3 ((*S,S*)*–*C*H$_3$), 23.8 ((*S,R*)*–*C*H$_3$), 34.0 ((*S,S*)*–*C*H$_2$), 35.6 ((*S,R*)*–*C*H$_2$), 47.6 ((*S,R*)*–*C*H), 47.9 ((*S,S*)*–*C*H), 69.9 ((*S,S*)*–*C*H), 70.1 ((*S,R*)*–*C*H), 90.7 (*C*C), 91.2 (*C*C), 101.2 (*C*C), 106.7 (*C*C), 127.8 (Ar*C*H), 128.1 (Ar*C*H), 128.9 (2xAr*C*H), 129.1 (2xAr*C*H), 129.3 (2xAr*C*H), 129.5 (2xAr*C*H), 137.4 (*C*Ar), 138.2 (*C*Ar), 199.2 (*C*O), 199.8 (*C*O); +ve; LRMS; LSIMS; pFAB (NOBA); m/z, calculated for C$_{31}$H$_{18}$Co$_4$O$_{12}$ [M–CO]$^+$; requires 817.8117, found 817.8282.

C$_{32}$H$_{16}$Co$_4$O$_{12}$
Mol. Wt.: 828.1950
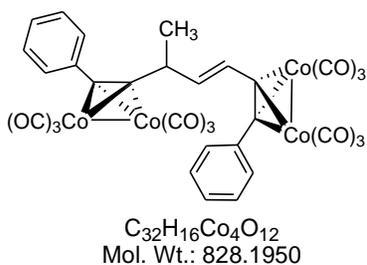
(*E*)–**(424)**.

(*E*)–**(424)**: IR (thin film) ν$_{max}$; 1605, 1481, 1443, 949 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.57 (3H, d, *J* 5.4 Hz, C*H*$_3$), 4.10 (1H, dq, *J* 8.1, 5.4 Hz, C*H*), 6.31 (1H, dd, *J* 14.8, 8.1 Hz, C*H*), 6.97 (1H, d, *J* 14.8 Hz, C*H*), 7.30–7.32 (6H, m, ArC*H*), 7.45–7.54 (4H, m, ArC*H*); δ$_C$ ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 23.0 (CH$_3$), 41.7 (CH), 89.5 (*C*≡C), 91.7 (*C*≡C), 92.6 (*C*≡C), 103.2 (*C*≡C), 127.3 (Ar*C*H), 127.8 (C=C), 127.9 (C=C), 128.9 (4xAr*C*H), 129.2 (2xAr*C*H), 129.4 (2xAr*C*H), 138.0

(*C*Ar), 138.3 (*C*Ar), 140.4 (Ar*C*H), 199.2 (*C*O), 199.7 (*C*O); +ve; LRMS; LSIMS; pFAB (NOBA); m/z, calculated for $C_{29}H_{16}Co_4O_9$; [M–3CO]$^+$= 743.8 (100).
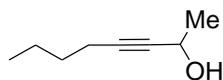
$C_8H_{14}O$
Mol. Wt.: 126.1962

Rac–**(426)**.

Compound *rac*–oct–3–yn–2–ol **(426)** was prepared from hex–1–yne (3.12 mL, 27.00 mmol) using the literature method [202], [233] and gave *rac*–**(426)** in 99%. The NMR data are in agreement with the literature and are given below for information.

Rac–**(426)**: δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 0.91 (3H, t, *J* 7.2 Hz, C*H*$_3$), 1.23–1.47(7H, m, C*H*$_3$, 2xC*H*$_2$), 1.79 (1H, m, O*H*), 2.20 (2H, m, C*H*$_2$), 4.51 (1H, m, C*H*); δ$_c$ ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 13.6 (*C*H$_3$), 18.3 (*C*H$_2$), 22.0 (*C*H$_2$), 24.8 (*C*H$_3$), 30.8 (*C*H$_2$), 58.5 (*C*H), 82.3 (*C*C), 84.5 (*C*C).
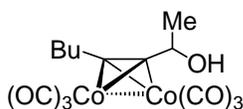
$C_{14}H_{14}Co_2O_7$
Mol. Wt.: 412.1232

Rac–**(427)**.

Compound *rac*–oct–3–yn–2–ol–3,4–dicobalt hexacarbonyl **(427)** was prepared from oct–3–yn–2–ol **(426)** (1.00 g, 7.95 mmol) using the literature method [174] to give *rac*–**(427)** in 94% yield. The NMR data are in agreement with the literature and are given below for information.

Rac–**(427)**: IR (thin film) v$_{max}$; 3419, 1602 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 0.97 (3H, t, *J* 7.4 Hz, C*H*$_3$), 1.43 (2H, m, C*H*$_2$), 1.49 (3H, d, *J* 6.2 Hz, C*H*$_3$), 1.62 (2H, m, C*H*$_2$), 1.75 (1H, d, *J* 4.9 Hz, O*H*), 2.82 (2H, t, *J* 7.4 Hz, C*H*$_2$), 4.99 (1H, m, C*H*); δ$_C$ ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 13.9 (*C*H$_3$), 22.8 (*C*H$_3$), 25.1 (*C*H$_2$), 33.5 (*C*H$_2$), 34.1 (*C*H$_2$), 68.5 (*C*H), 98.8 (*C*C), 102.5 (*C*C), 200.0 (*C*O).

(*S,S*)*-**(428)** *anti*

$C_{28}H_{26}Co_4O_{13}$
Mol. Wt.: 806.2310

(*S,R*)*-**(428)** *syn*
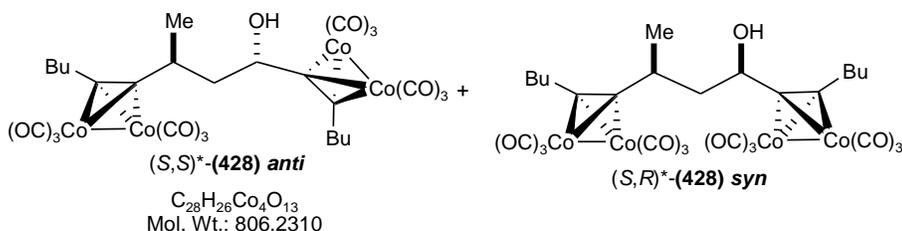
Schlenk tube (250 mL) was charged with *rac*–**(427)** (1.00 g, 2.43 mmol) dissolved in the minimum amount of Et$_2$O (3 mL) cooled to –35°C. HBF$_4$ (1.20 mL, 14.60 mmol) added and allowed to stir for *ca.* 8 hours until being warmed to room temp., aqueous work up with equal portions CH$_2$Cl$_2$/H$_2$O to give **(428)** (0.31 g, 31%, *d.r.*= 4 (*S,S*)*:1 (*S,R*)*), **(429)** (0.10

g, 10%, *d.r.*= >6.5 (*S,S*)*:1 (*S,R*)*) and (*E*)–**(430) (**0.17 g,17%) as a burgundy coloured solids after silica gel column chromatography 1:19 EtOAc/CH$_2$Cl$_2$.

(428): IR (thin film) ν_{max}; 3351, 1705 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 0.96, (6H, d, *J* 7.4 Hz, 2xC*H*$_3$), 1.37 (3H, d, *J* 6.7 Hz, C*H*$_3$), 1.40–1.50 (5H, m, O*H*, 2xC*H*$_2$), 1.53–1.70 (4H, m, C*H*$_2$), 1.72 (1H, m, C*H*$_2$), 2.02 (1H, ddd, *J* 13.9, 10.9, 3.0 Hz, C*H*$_2$), 2.70–2.87 (4H, m, 2xC*H*$_2$), 3.35 (1H, m, C*H*), 4.94 (1H, m, (*S,S*)*–C*H*), 5.00 (1H, m, (*S,R*)*–C*H*); δ$_C$ ^{13}C NMR (δ, 67 MHz, CDCl$_3$); δ$_C$ ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 13.8, 20.9, 22.7, 22.8, 23.5, 33.2, 33.5, 33.7, 34.1, 35.4, 47.8 , 69.6, 71.4, 98.5, 98.7, 100.1, 100.6, 101.2, 105.3, 106.2, 199.8 (*CO*), 200.4 (*CO*); +ve; LRMS; LSIMS; pFAB (NOBA); m/z, calculated for C$_{23}$H$_{26}$Co$_4$O$_8$; [M–5CO]$^+$ = 665.9 (100).

(*S,S*)*-**(429)** *anti*

C$_{30}$H$_{30}$Co$_4$O$_{13}$
Mol. Wt.: 834.2842

(*S,R*)*-**(429)** *syn*
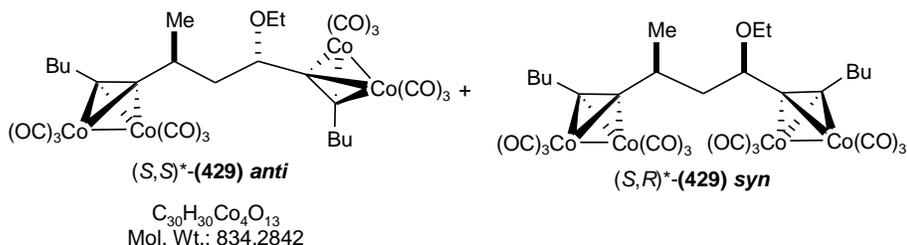
(429): m.p. 50–52°C; Anal Calc. for C$_{30}$H$_{30}$Co$_4$O$_{13}$; Calc.; C, 43.19: H, 3.62; Found; C, 43.40; H, 3.73; IR (thin film) ν_{max}; 1607 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 0.96, (6H, d, *J* 7.2 Hz, 2xC*H*$_3$), 1.23 (3H, d, *J* 6.9 Hz, C*H*$_3$), 1.34 (3H, d, *J* 6.7 Hz, C*H*$_3$), 1.39–1.50 (4H, m, 2xC*H*$_2$), 1.51–1.72 (5H, m, 2xC*H*$_2$, (C*H*^{1})$_2$), 2.11 (1H, ddd *app* t, *J* 13.5 Hz, (C*H*^{2})$_2$), 2.82 (4H, m, 2xC*H*$_2$), 3.23 (1H, m, C*H*), 3.58 (1H, dq, *J* 6.9 Hz, C*H*$_2$), 3.87 (1H, dq, *J* 6.9 Hz, C*H*$_2$), 4.53, (1H, dd, *J* 10.6, 1.7 Hz, C*H*); δ$_C$ ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 13.9, 15.3, 21.2, 23.3 (*S,R*)*, 22.8, 33.8, 34.0, 34.1, 34.2, 35.9 (*S,R*)*, 46.0 (*S,R*)*, 46.9, 66.0 (*S,R*)*, 66.6, 77.3, 78.7, 98.5 (C*C*), 99.4 (C*C*), 100.2 (C*C*), 106.5 (C*C*), 200.1 (*CO*), 200.4 (*CO*); +ve; HRMS; pFAB (NOBA); m/z, calculated for C$_{30}$H$_{30}$Co$_4$O$_{13}$; [M]$^+$; requires 833.9016, found 833.9192 .

C$_{28}$H$_{24}$Co$_4$O$_{12}$
Mol. Wt.: 788.2158
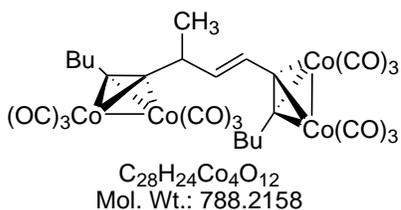
(*E*)–**(430)**.

(430): δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$) 0.96 (6H, t, *J* 7.2 Hz, 2xC*H*$_3$), 1.41–1.69 (11H, m, nC*H*$_2$, nC*H*$_3$), 2.77–2.90 (4H, m, 2xC*H*$_2$), 3.74 (1H, m, C*H*), 6.06 (1H, dd, *J* 14.8, 8.2 Hz, C*H*), 6.63 (1H, d, *J* 14.8 Hz, C*H*). The ^{1}H NMR shows decomposition, HRMS could not be obtained due to non homogeneity in the sample.

(*S,S*)*-**(432)**
C$_{43}$H$_{24}$Co$_4$O$_{14}$
Mol. Wt.: 1000.3751
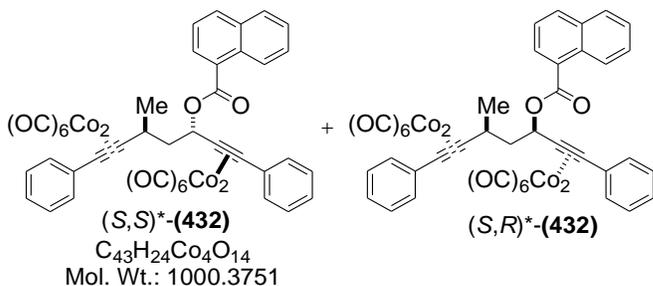
(432).

Compound **(432)** was prepared from **(423)** *d.r.*= 4 (*S,S*)*:1 (*S,R*)* (0.30 g, 0.35 mmol) and 1–naphthalenecarboxylic acid **(431)** (0.06 g, 0.35 mmol) using the literature method [205] to give **(432)** (0.28 g, 82%, *d.r.*= 14 (*S,S*)*:3 (*S,R*)*) as a burgundy oil purified 1:19 CH$_2$Cl$_2$/petroleum ether (40–60°C).

(432): IR (thin film) v$_{max}$; 1714 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.45 (3H, d, *J* 6.7 Hz, (*S,R*)*–C*H*$_3$), 1.60 (3H, d, *J* 6.7 Hz, (*S,S*)*–C*H*$_3$), 2.13 (1H, ddd, *J* 13.6, 11.4, 2.0 Hz, C*H*$_2$), 2.65 (1H, ddd, *J* 13.6, 11.4, 2.0 Hz, C*H*$_2$), 3.50 (1H, m, (*S,S*)*–C*H*), 3.52 (1H, m, (*S,R*)*–C*H*), 7.03 (1H, dd, *J* 11.1, 1.7 Hz, ArC*H*), 7.27–7.33 (8H, m, ArC*H*), 7.41–7.65 (5H, m, ArC*H*), 7.89 (1H, dd, *J* 7.2, 1.2 Hz, ArC*H*), 8.05 (1H, d, *J* 7.2 Hz, ArC*H*), 8.32 (1H, dd, *J* 7.4, 1.0 Hz, (*S,S*)*–ArC*H*), 8.35 (1H, dd, *J* 7.4, 1.0 Hz, (*S,R*)*–ArC*H*), 9.04 (1H, dd, *J* 7.4, 1.0 Hz, (*S,S*)*–ArC*H*), 9.09 (1H, d, *J* 7.4 Hz, (*S,R*)*–ArC*H*); δ$_C$ ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 21.7((*S,S*)*–CH$_3$), 23.1 ((*S,R*)*–CH$_3$), 29.8 ((*S,S*)*–CH$_2$), 34.4 ((*S,S*)*–CH$_2$), 36.8 ((*S,R*)*–CH$_2$), 41.2 ((*S,R*)*–CH), 46.6 ((*S,S*)*–CH), 71.9 ((*S,S*)*–CH), 74.8 ((*S,R*)*–CH), 90.9 ((*S,S*)*–CC), 91.2 ((*S,S*)*–CC), 91.7 ((*S,R*)*–CC), 95.8 ((*S,S*)*–CC), 105.7 ((*S,S*)*–CC), 124.5 (Ar), 125.8 (Ar), 126.4 (Ar), 127.9 (Ar), 128.2 (Ar), 128.8 (Ar), 129.0 (2xAr), 129.3 (Ar), 129.5 (Ar), 130.6 (Ar), 130.8 (Ar), 131.9 (Ar), 134.1 (Ar), 134.4 (Ar), 137.3 (Ar), 137.4 (Ar), 138.1 (Ar), 166.6 (Ar), 166.7 (Ar), 198.8 (*CO*), 199.1 (*CO*), 199.6 (*CO*); +ve; LRMS; LSIMS; pFAB (NOBA); m/z, calculated for C$_{40}$H$_{24}$O$_{11}$Co$_4$; [M–3CO]$^+$= 915.9 (100).

(*S,S*)*-**(433)**
C$_{20}$H$_{18}$O
Mol. Wt.: 274.3563
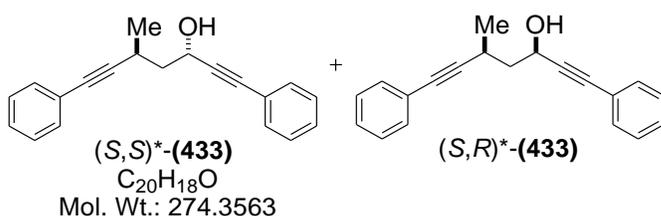
5–Methyl–1,7–diphenylhepta–1,6–diyn–3–ol, **(433)**.

Compound **(433)** was prepared by demetallation using the literature method [231], [232] using **(423)** (0.40 g, 0.47 mmol) and gave **(433)** (0.19 g, 72%, *d.r.*= 5 (*S,S*)*:1 (*S,R*)*) as a colourless oil after silica gel column chromatography using 3:7 EtOAc/hexane.

(433): IR (thin film) v$_{max}$; 2203, 1670, 1490 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.28 (3H, d, *J* 7.2 Hz, C*H*$_3$), 1.85–2.10 (3H, m, O*H*, C*H*$_2$), 2.89 (1H, m, (*S,S*)*–C*H*), 2.91 (1H, m, (*S,R*)*–C*H*), 4.82 (1H, m, C*H*), 7.19–7.26 (6H, m, ArC*H*), 7.32–7.39 (4H, m, ArC*H*); δ$_C$ ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 21.4 ((*S,S*)*–CH$_3$), 23.9 ((*S,S*)*–CH$_2$), 45.0 ((*S,R*)*–CH), 45.1 ((*S,S*)*–CH), 61.5 ((*S,R*)*–(CH), 62.2 ((*S,S*)*–(CH)), 81.8 ((*S,S*)*–CC}, 82.2 ((*S,R*)*–CC), 85.6 (CC), 89.8 ((*S,S*)*–

CC), 90.1 ((*S,R*)*–*CC*), 93.3 ((*S,R*)*–*CC*), 93.4 ((*S,S*)*–*CC*), 122.7 (*C*Ar), 123.8 (*C*Ar), 128.0 (Ar*C*H), 128.4 (2xAr*C*H), 128.5 (2xAr*C*H), 128.7 (Ar*C*H), 131.0 (2xAr*C*H), 132.0 (2xAr*C*H); +ve; HRMS; CI(P), m/z, calculated for $C_{20}H_{17}O$; [M–H]$^+$; requires 273.1274, found 273.1279.

(*S,S*)*-**(434)**   +   (*S,R*)*-**(434)**
$C_{21}H_{20}O$
Mol. Wt.: 288.3829
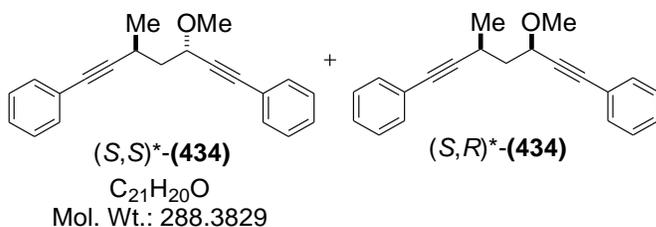
3–Methoxy–5–methyl hepta–1,6–diyne–1,7–diyl dibenzene, **(434)**.

Compound **(434)** was prepared by demetallation using the literature method [231], [232] from **(421)** (0.37 g, 0.43 mmol) and gave **(434)** (0.17 g, 69%, *d.r.*= 4 (*S,S*)*:1 (*S,R*)*) as a colourless oil after silica gel column chromatography using 3:7 EtOAc/hexane.

(434): IR (thin film) v_{max}; 2968, 2361, 1491, 1103 cm^{-1}; δ_H ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.31 (3H, d, *J* 8.0 Hz, (*S,R*)*–C*H*$_3$), 1.34 (3H, d, *J* 6.8 Hz, (*S,S*)*–C*H*$_3$), 1.89–2.00 (1H, m, C*H*$_2$), 2.06–2.14 (1H, m, C*H*$_2$), 2.99 (1H, m, C*H*), 3.48 (3H, s, (*S,S*)*–OC*H*$_3$), 3.52 (3H, s, (*S,R*)*–OC*H*$_3$), 4.44 (1H, m, (*S,S*)*–C*H*), 4.45 (1H, m, (*S,R*)*–C*H*), 7.28–7.32 (6H, m, Ar*C*H*), 7.40–7.43 (2H, m, Ar*C*H*), 7.44–7.48 (2H, m, Ar*C*H*); δ_C ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 20.1 (*C*H$_3$), 22.3 (*C*H$_2$), 41.5 ((*S,S*)*–*C*H), 42.2 ((*S,R*)*–*C*H), 55.1 ((*S,S*)*–*C*H), 55.8 ((*S,R*)*–*C*H), 68.7 ((*S,R*)*–O*C*H$_3$), 69.4 ((*S,S*)*–O*C*H$_3$), 80.2 ((*S,S*)*–*CC*), 80.5 ((*S,R*)*–*CC*), 84.7 ((*S,R*)*–*CC*), 85.5 ((*S,S*)*–*CC*), 86.5 ((*S,S*)*–*CC*), 87.0 ((*S,R*)*–*CC*), 92.12 ((*S,R*)*–*CC*), 92.4 ((*S,S*)*–*CC*), 121.6 (*C*Ar), 122.7 (*C*Ar), 126.6 (Ar*C*H), 127.1 (2xAr*C*H), 127.2 (2xAr*C*H), 127.3 (Ar*C*H), 130.5 (2xAr*C*H), 130.8 (2xAr*C*H); +ve, HRMS, CI(P), m/z, calculated for $C_{21}H_{24}ON$; [M+NH$_4$]$^+$; requires 306.1852, found 306.1858.

(*S,S*)*-**(435)**   +   (*S,R*)*-**(435)**
$C_{16}H_{26}O$
Mol. Wt.: 234.3770
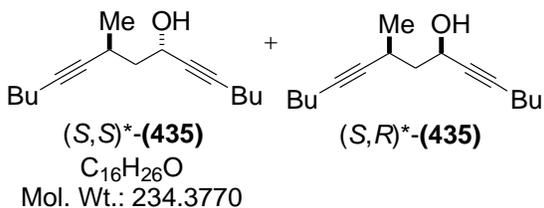
9–Methylpentadeca–5,10–diyn–7–ol, **(435)**.

Compound **(435)** was prepared by demetallation using the literature method [231], [232] from **(428)** (0.20 g, 0.25 mmol) and gave **(435)** (0.07 g, 99%, *d.r.*= 5:1) as a colourless oil after filtration through celite.

(435): IR (thin film) v_{max}; 3340, 2236 cm^{-1}; δ_H ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 0.88 (6H, td, *J* 6.9, 1.7 Hz, 2xC*H*$_3$), 1.15 (3H, d, *J* 6.9 Hz, (*S,R*)*–C*H*$_3$), 1.17 (3H, d, *J* 6.9 Hz, (*S,S*)*–C*H*$_3$), 1.30–1.53 (9H, m, O*H*, 4xC*H*$_2$), 1.60–1.88 (2H, m, C*H*$_2$), 2.90–2.22 (4H, m, 2xC*H*$_2$), 2.57 (1H, m, (*S,S*)*–C*H*), 2.75 (1H, m, (*S,R*)*–C*H*), 4.53 (1H, m, C*H*); δ_C ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 13.6 (2x*C*H$_3$), 18.4 (2x*C*H$_2$), 21.6 (*C*H$_2$), 21.7 (*C*H$_2$), 22.0 (2x*C*H$_2$), 23.3 (*C*H$_2$), 30.8 (*C*H$_2$), 31.2 (*C*H$_2$),

45.3 ((*S,R*)*–*C*H), 45.7 ((*S,S*)*–*C*H), 61.2 ((*S,R*)*–*C*H), 62.0 ((*S,S*)*–*C*H), 80.9 (*CC*), 81.1 (*CC*), 81.5 (*CC*), 83.7 (*CC*),

85.8 (*CC*); +ve; HRMS, ESI, m/z, calculated for $C_{16}H_{30}ON$; $[M+NH_4]^+$; requires 252.2322, found 252.2322.
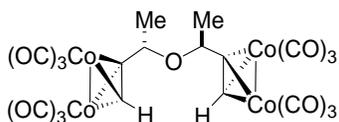
$C_{20}H_{10}Co_4O_{13}$
Mol. Wt.: 694.0184

(*S, S*)*–**(436)**.

Using the general procedure in **section 5.5** *rac*–**(386)** (0.50 g, 1.40 mmol) and **(387b)** (0.60 g, 1.40 mmol) gave (*S,S*)*–**(436)** as a burgundy coloured solid (0.78 g, 80%) after purification using silica gel column chromatography with a 3:7 EtOAc/hexane.

(*S,S*)*–**(436)**: m.p. 66–68°C; Anal. Calc. for $C_{20}H_{10}O_{13}Co_4$; Calc; C, 34.61: H, 1.45; Found; C, 34.51; H, 1.41; IR (thin film) v_{max}; 1530 cm^{-1}; $δ_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.51 (6H, d, *J* 6.2 Hz, C*H$_3$*), 4.96 (2H, q, *J* 6.2 Hz, C*H*), 6.06 (2H, s, C*H*); $δ_C$ ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 23.6 (2xCH$_3$), 72.9 (2xCH), 73.2 (2xCH), 96.8 (2xC*C*), 199.6 (2xC*O*); +ve; LRMS; LSIMS; pFAB (NOBA); m/z, calculated for $C_{17}H_{10}Co_4O_{10}$; $[M–3CO]^+$= 609.7 (100), calculated for $C_{15}H_{10}Co_4O_8$; $[M–5CO]^+$= 553.7 (100).
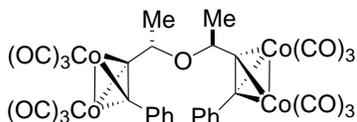
$C_{32}H_{18}Co_4O_{13}$
Mol. Wt.: 846.2103

(*S, S*)*–**(437)**.

Using the general procedure in **section 5.5** *rac*–**(392)** (1.50 g, 1.73 mmol) and **(409b)** (0.89 g, 1.73 mmol) gave (*S,S*)*–**(437)** (1.26 g, 86%) as a burgundy coloured solid after purification using silica gel column chromatography with a 3:7 EtOAc/hexane.

(*S,S*)*–**(437)**: m.p. 108–110°C; Anal. Calc. for $C_{32}H_{18}O_{13}Co_4$; Calc.; C, 45.40: H, 2.14; Found; C, 45.40; H, 2.51; IR (thin film) v_{max}; 1608 cm^{-1}; $δ_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.58 (6H, d, *J* 6.7 Hz, 2xC*H$_3$*), 5.13 (2H, q, *J* 6.7 Hz, 2xC*H*), 7.26–7.31 (6H, m, ArC*H*), 7.49–7.54 (4H, m, ArC*H*); $δ_C$ ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 22.8 (2xCH$_3$), 75.9 (2xCH), 91.7 (2xC*C*), 99.5 (2xCC), 127.8 (2xArC*H*), 128.8 (4xArC*H*), 129.8 (4xArC*H*), 138.0 (2xCAr), 199.5 (2xCO); +ve; LRMS; LSIMS; pFAB (NOBA); m/z, calculated for $C_{26}H_{18}Co_4O_7$; $[M–6CO]^+$= 677.9 (100).

$C_{28}H_{26}Co_4O_{13}$
Mol. Wt.: 806.2310
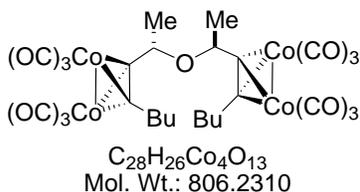
(*S,S*)*–**(438)**.

Using the general procedure in **section 5.3** *rac*–**(427)** (0.50 g, 1.22 mmol) but using *rac*–**(427)** (0.50 g, 1.22 mmol) again as the nucleophile gave (*S,S*)*–**(438)** (0.59 g, 61%) as a burgundy coloured oil after purification using silica gel column chromatography with a 3:7 EtOAc/hexane.

(*S,S*)*–**(438)**: IR (thin film) v$_{max}$; 1602 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 0.97 (6H, t, *J* 7.4 Hz, 2xC*H*$_3$), 1.43–1.53 (10H, m, 2xC*H*$_3$, 2xC*H*$_2$), 1.58–167 (4H, m, 2xC*H*$_2$), 2.82 (4H, t, *J* 7.4 Hz, 2xC*H*$_2$), 4.85 (2H, m, C*H*); δ$_C$ ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 13.9 (2xCH$_3$), 22.6 (2xCH$_2$), 22.8 (2xCH$_3$), 33.5 (2xCH$_2$), 34.2 (2xCH$_2$), 75.0 (2xCH), 99.2 (2xCC), 99.7 (2xCC), 200.1 (2xCO); +ve; LRMS; LSIMS; pFAB (NOBA); calculated for C$_{25}$H$_{26}$Co$_4$O$_{10}$; [M–3CO]$^+$= 721.9 (100).

$C_{15}H_{12}O$
Mol. Wt.: 208.2552
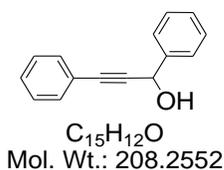
Rac–1,3–diphenyl–prop–2–yn–1–ol, **(442)**.

Compound *rac*–1,3–diphenyl–prop–2–yn–1–ol **(442)** was prepared from phenylacetylene (3.00 mL, 27.00 mmol) using the literature method [161], [234] and gave *rac*–**(442)** in 99% yield. The NMR data are in agreement with the literature and are given below for information.

Rac–**(442)**: δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 4.13 (1H, brs, O*H*), 5.66 (1H, s, C*H*), 7.30–7.5 (8H, m, ArC*H*), 7.60–7.64 (2H, m, ArC*H*); δ$_c$ ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 65.2 (CH), 86.74 (CC), 89.0 (CC), 126.1 (CAr), 126.9 (CAr), 128.4 (ArCH), 128.5 (ArCH), 128.7 (ArCH), 128.8 (2xArCH), 131.9 (4xArCH), 140.8 (CAr).

$C_{21}H_{12}Co_2O_7$
Mol. Wt.: 494.1822
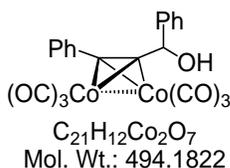
Rac–1,3–diphenyl–prop–2–yn–1–ol–3,4–dicobalt hexacarbonyl, **(443)**.

Compound *rac*–**(443)** was prepared from *rac*–**(442)** (1.00 g, 4.80 mmol) using the literature method [228] and gave *rac*–**(443)** in 80% yield. The NMR data are in agreement with the literature and are given below for information.

Rac–**(443)**: IR (thin film) v$_{max}$; 3452, 1605 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 2.45 (1H, brs, O*H*), 6.14 (1H, brs, C*H*) 7.26–7.39 (6H, m, ArC*H*), 7.46–7.56 (4H, m, ArC*H*); δ$_C$ ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 74.7 (CH), 91.6 (CC), 102.1 (CC),

126.0 (*C*Ar), 127.9 (*C*Ar), 128.4 (2xAr*C*H), 128.7 (Ar*C*H), 128.9 (Ar*C*H), 129.6 (Ar*C*H), 137.9 (4xAr*C*H), 144.1 (*C*Ar), 199.1 (*C*O); +ve; LRMS; LSIMS; pFAB (NOBA), m/z, calculated for $C_{21}H_{12}Co_2O_7$; [M]$^+$= 493.9 (10), [M–CO]$^+$= 465.9 (30), [M–2CO]$^+$ = 437.9 (25), [M–3CO]$^+$= 409.9 (20), [M–4CO]$^+$= 381.8 (100), [M–5CO]$^+$= 353.8 (20), [M–6CO]$^+$= 325.8 (30).
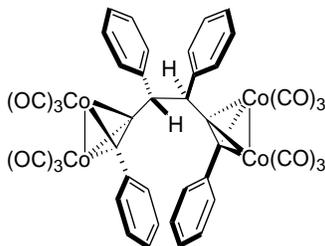
$C_{42}H_{22}Co_4O_{12}$
Mol. Wt.: 954.3497

(*S,S*)*–**(446)**.

Schlenk tube (250 mL) was charged with **(444)** (1 equiv.) which was created *in situ* from **(443)** using HBF$_4$ (2 equiv.), **(443)** (0.50 g, 1.01 mmol) added at –35°C, stirred for 1 hour then purified as in **section 5.3**. to give **(446)** (0.65 g, 67%, *d.r.*=12:1) as a red solid, recrystallised using 3:7 EtOAc/hexane to give (*S,S*)*–**(446)**.

(*S,S*)*–**(446)**: m.p. 148–150°C; Anal. Calc. for $C_{42}H_{22}O_{12}Co_4$; Calc.; C, 52.84; H, 2.32; Found; C, 52.83; H, 2.35; IR (thin film) v_{max}; 1601 cm^{-1}; δ_H ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 5.15 (2H, s, 2xC*H*), 6.93–7.07 (12H, m, ArC*H*), 7.13–7.22 (8H, m, ArC*H*); δ_C^{13}C NMR (δ, 67 MHz, CDCl$_3$); 60.5 (2x*C*H), 93.0 (2x*C*C), 103.2 (2x*C*C), 127.6 (2xAr*C*H), 128.0 (6xAr*C*H), 128.6 (4xAr*C*H), 130.0 (4xAr*C*H), 131.5 (4xAr*C*H), 138.2 (2xAr*C*), 140.8 (2xAr*C*), 198.9 (*C*O), 199.9 (*C*O); LRMS; EI; m/z, calculated for $C_{39}H_{22}Co_4O_9$; [M–3CO]$^+$= 869.9 (100).
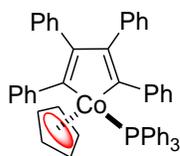
$C_{51}H_{40}CoP$
Mol. Wt.: 742.7703

(η^5–Cyclopentadienyl)(triphenylphosphine)cobaltacyclopentadiene complex, **(489a)**.

Using the general procedure in **section 5.71a(i)**, diphenylacetylene (0.40 g, 2.25 mmol), gave complex **(489a)** (0.75 g, 90%) as a crystalline red solid after silica gel column chromatography using 3:7 EtOAc/hexane.

(489a): m.p. 208–210°C; IR (thin film) v_{max}; 737, 702 cm^{-1}; δ_H^{1}H NMR (δ, 270 MHz, CDCl$_3$); 4.76 (5H, s, C$_5$*H*$_5$), 6.41–6.53 (8H, m, ArC*H*), 6.70–6.92 (12H, m, ArC*H*), 7.13–7.42 (15H, m, ArC*H*); δ_C ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 89.7 (*C*$_5$H$_5$), 123.2, 123.7, 126.2 (Ar), 126.8 (Ar), 128.2 (Ar), 128.3 (Ar), 129.1 (Ar), 129.8 (Ar), 130.5 (Ar), 133.6 (Ar), 133.7 (Ar), 142.1 (Ar), 153.6 (Ar), 157.7 (Ar); δ_P ^{31}P NMR (δ, 104 MHz, CDCl$_3$); 52.2; HRMS; ESI; m/z, calculated for $C_{33}H_{25}Co$; [M–PPh$_3$]$^+$; requires 480.1281, found 480.1283.
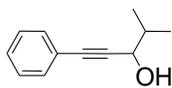
$C_{12}H_{14}O$
Mol. Wt.: 174.2390

Rac–**(498)**.

Compound *rac*–4-methyl–1–phenyl–pent–1–yn–3–ol **(498)** was prepared from phenylacetylene (3.00 mL, 27.00 mmol) using the literature method [161] and gave *rac*–**(498)** in 99% yield. The NMR data are in agreement with the literature and are given below for information.

Rac–**(498)**: IR (thin film) v_{max}; 3420 cm^{-1}; δ_H ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.07 (3H, d, *J* 6.9 Hz, C*H*$_3$), 1.12 (3H, d, *J* 6.9 Hz, C*H*$_3$), 1.98 (1H, m, C*H*), 3.03 (1H, d, *J* 5.4 Hz, O*H*), 4.41 (1H, d, *J* 5.4 Hz, C*H*), 7.21– 7.29 (3H, m, ArC*H*), 7.43– 7.44 (2H, m, ArC*H*); δ_c ^{13}C NMR (67 MHz, CDCl$_3$); 17.7 (*C*H$_3$), 18.4 (*C*H$_3$), 34.8 (*C*H(CH$_3$)$_2$), 68.4 (*C*HOH), 85.6 (*C*C), 89.2 (*C*C), 122.9 (*C*Ar), 128.4 (3xAr*C*H), 131.8 (2xAr*C*H).
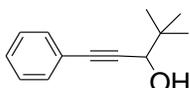
$C_{13}H_{16}O$
Mol. Wt.: 188.2655

Rac–**(499)**.

Compound 4,4–dimethyl–1–phenylpent–1–yn–3–ol **(499)** was prepared from phenylacetylene (3.00 mL, 27.00 mmol) using the literature method [161], [234] and gave *rac*–**(499)** in 95% yield. The NMR data are in agreement with the literature and are given below for information.

Rac–**(499)**: IR (thin film) v_{max}; 3380 cm^{-1}; δ_H ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.06 (9H, s, ((C*H*$_3$)$_3$CH), 2.79 (1H, brs, O*H*), 4.28 (1H, s, C*H*), 7.27–7.29 (3H, m, ArC*H*), 7.43–7.69 (2H, m, ArC*H*); δ_c ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 26.1 ((CH$_3$)$_3$*C*), 36.2 ((CH$_3$)$_3$*C*), 71.8 (*C*H), 85.7 (*C*C), 89.4 (*C*C), 123.1 (*C*Ar), 128.3 (2xAr*C*H), 128.4 (2xAr*C*H), 131.8 (Ar*C*H).
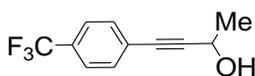
$C_{11}H_9F_3O$
Mol. Wt.: 214.1838

Rac–**(500)**.

Compound 4–(4–trifluoromethyl–phenyl)–but–3–yn–2–ol **(500)** was prepared from 1–ethynyl–4–(trifluoromethyl)benzene (2.37 mL, 13.5 mmol) using the literature method [202] and gave *rac*–**(500)** in 91% yield. The NMR data are in agreement with the literature and are given below for information.

Rac–**(500)**: IR (thin film) v_{max}; 3273 cm^{-1}; δ_H ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.50 (3H, d, *J* 6.7 Hz, C*H*$_3$), 2.02 (1H, brs, O*H*), 4.70 (1H, q, *J* 6.7 Hz, C*H*), 7.43–7.58 (4H, m, ArC*H*); δ_c ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 24.2 (*C*H$_3$), 58.6 (*C*H), 82.6

(*CC*), 93.7 (*CC*), 125.2 (2xAr*CH*), 125.9 (q, *J* 33.0 Hz, Ar*CF₃*), 126.6 (*C*Ar), 131.9 (2xAr*CH*), 132.4 (*C*Ar); δ_F ¹⁹F NMR (δ, 376 MHz, CDCl₃); –64.2 (C*F₃*); HRMS, EI, for $C_{11}H_9FO$; [M]⁺; requires 214.0600, found 214.0597.
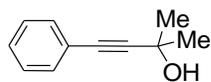
$C_{11}H_{12}O$
Mol. Wt.: 160.2124

(501).

Compound *rac–2–methyl–4–phenyl–but–3–yn–2–ol* **(501)** was prepared from phenylacetylene (3.00 mL, 27.00 mmol) using the literature method [161], [235] and gave *rac*–**(501)** in 94% yield. The NMR data are in agreement with the literature and are given below for information.

(501): δ_H ¹H NMR (δ, 270 MHz, CDCl₃); 1.59 (6H, s, 2xC*H₃*), 2.68 (1H, brs, O*H*), 7.25–7.27 (3H, m, Ar*CH*), 7.39–7.50 (2H, m, Ar*CH*); δ_c ¹³C NMR (δ, 67 MHz, CDCl₃); 31.7 (2xC*H₃*), 65.8 (*C*(CH₃)₂), 82.3 (*CC*), 94.1 (*CC*), 123.0 (Ar*CH*), 128.4 (3xAr*CH*), 131.8 (2xAr*CH*).
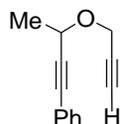
$C_{13}H_{12}O$
Mol. Wt.: 184.2338

Rac–**(502)**.

Compound *rac*–(3–(prop–2–ynyloxy)but–1–ynyl benzene **(502)** was prepared from *rac*–**(391)** (2.00 g, 15.03 mmol) using the literature method [161], and gave *rac*–**(502)** in 72% yield. The NMR data are in agreement with the literature and are given below for information. An alternative method known in the literature [203] gave *rac*–**(502)** in 99% yield.

Rac–**(502)**: δ_H ¹H NMR (δ, 270 MHz, CDCl₃); 1.56 (3H, d, *J* 6.7 Hz, C*H₃*CH), 2.45 (1H, td, *J* 2.5, 1.0 Hz, C*H*), 4.32 (1H, dd, *J* 15.7, 2.5 Hz, C*H₂*O), 4.35 (1H, dd, *J* 15.7, 2.5 Hz, C*H₂*O), 4.64 (1H, q, *J* 6.7 Hz, CH₃C*H*), 7.30–7.33 (3H, m, Ar*CH*), 7.43–7.47 (2H, m, Ar*CH*); δ_C ¹³C NMR (δ, 67 MHz, CDCl₃); 22.2 (*CH₃*), 55.9 (*CH₂*), 64.7 (*CH*), 74.6 (*CC*), 79.7 (*CC*), 85.8 (*CC*), 88.1 (*CC*), 122.6 (*C*Ar), 128.4 (2xAr*CH*), 128.6 (Ar*CH*), 131.9 (2xAr*CH*).
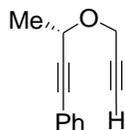
$C_{13}H_{12}O$
Mol. Wt.: 184.2338

(*S*)–(–)–**(502)**.

Compound (*S*)–(–)–(3–(prop–2–ynyloxy)but–1–ynyl benzene **(502)** was prepared from (*S*)–(–)–**(391)** (1.00 g, 6.84 mmol) using the literature method [203] and gave (*S*)–(–)–**(502)** in 99% yield.

(*S*)–(–)–**(502)**: [α]$_D$= –176.1 (*c* 0.044 , 23.0°C, CHCl$_3$); ^{1}H NMR (δ, 400 MHz, CDCl$_3$) 1.45 (3H, d, *J* 7.2 Hz, C*H*$_3$), 2.35 (1H, td, *J* 2.4, 0.4 Hz, C*H*), 4.32 (1H, dd, *J* 15.6, 2.4 Hz, C*H*$_2$O), 4.35 (1H, dd, *J* 15.6, 2.4 Hz, C*H*$_2$O), 4.53 (1H, q, *J* 7.2 Hz, C*H*), 7.19–7.23 (3H, m, ArC*H*), 7.32–7.36 (2H, m, ArC*H*); ^{13}C NMR (δ, 100 MHz, CDCl$_3$) 22.3 (*C*H$_3$), 56.0 (*C*H$_2$), 64.8 (*C*H), 74.7 (*C*C), 79.8 (*C*C), 85.9 (*C*C), 88.2 (*C*C), 122.7 (*C*Ar), 128.5 (2xAr*C*H), 128.7 (Ar*C*H), 132.0 (2xAr*C*H); +ve; HRMS; ESI; m/z, calculated for C$_{13}$H$_{16}$ON; [M+NH$_4$]$^+$; requires 202.1226, found 202.1224; HPLC (CHIRALCEL OD) 96.5:3.5 hexane/isopropyl alcohol, 1 mL/ min R$_t$=5 min 0 secs.

i-Pr

Ph H

C$_{15}$H$_{16}$O
Mol. Wt.: 212.2869
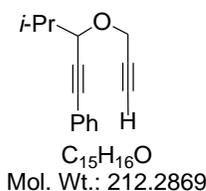
Rac–**(503)**.

Compound *rac*–(4–methyl–3–prop–2–ynyloxy)–pent–1–ynyl–benzene **(503)** was prepared from *rac*–**(498)** (1.66 g, 9.50 mmol) using the literature method [161] and gave *rac*–**(503)** in 82% yield. The NMR data are in agreement with the literature and are given below for information.

Rac–**(503)**: δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.08 (3H, d, *J* 6.4 Hz, C*H*$_3$), 1.10 (3H, d, *J* 6.4 Hz, C*H*$_3$), 2.00–2.12 (1H, m, C*H*), 2.45 (1H, t, *J* 2.5 Hz, CC*H*), 4.33 (1H, d, *J* 6.4 Hz, C*H*), 4.34 (1H, dd, *J* 15.6, 2.5 Hz, C*H*$_2$), 4.43 (1H, dd, *J* 15.6, 2.5 Hz, C*H*$_2$), 7.30–7.33 (3H, m, ArC*H*), 7.44–7.52 (2H, m, ArC*H*); δ$_c$ ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 18.0 (*C*H$_3$), 18.7 (*C*H$_3$), 33.3 (*C*H$_2$), 56.1 (*C*H), 74.4 (*C*H), 74.5 (*C*H), 79.9 (*C*C), 86.3 (*C*C), 87.1 (*C*C), 122.8 (*C*Ph), 128.3 (2xAr*C*H), 128.4 (Ar*C*H), 131.9 (2xAr*C*H).

O

Ph H

C$_{12}$H$_{10}$O
Mol. Wt.: 170.2072
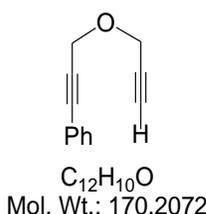
(504).

Compound (3–(prop–2–ynyloxy)prop–1–ynyl)benzene **(504)** was prepared from **(397)** (1.00 g, 7.58 mmol) using the literature method [203] and gave **(504)** in 99% yield. The NMR data are in agreement with the literature and are given below for information. [Compound **(505)** was observed as a by product on a separate occasion].

(504): δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$) 2.39 (1H, t, *J* 2.4 Hz, C*H*), 4.22 (2H, d, *J* 2.4 Hz, C*H*$_2$), 4.39 (2H, s, C*H*$_2$), 7.18–7.23 (3H, m, ArC*H*), 7.35–7.37 (2H, m, ArC*H*); δ$_C$ ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 56.7 (*C*H$_2$), 57.5 (*C*H$_2$), 75.3 (*C*C), 79.3 (*C*C), 84.3 (*C*C), 87.1 (*C*C), 122.6 (*C*Ar), 128.6 (2xAr*C*H), 128.8 (2xAr*C*H), 132.0 (Ar*C*H).
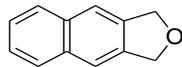
C$_{12}$H$_{10}$O
Mol. Wt.: 170.2072

1,3–Dihydronaphtho[2,3–c]furan, **(505)**.

(505): m.p. 152–154°C; δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 5.25 (4H, s, CH_2), 7.38 (2H, m, ArCH), 7.59, (2H, s, ArCH), 7.95 (2H, s, ArCH); δ$_c$ ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 72.8 (2xArCH), 119.3 (2xArCH), 125.8 (2xArCH), 127.9 (2xArCH), 133.2 (2xCAr), 138.3 (2xCAr).
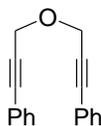
C$_{18}$H$_{14}$O
Mol. Wt.: 246.3032

3,3'–Oxybis(prop–1–yne–3,1–diyl)dibenzene, **(519)**.

Using the modified literature method $^{(161)}$ in **section 5.6** (3–(prop–2–ynyloxy)prop–1–ynyl)benzene **(504)** (0.50 g, 2.94 mmol) and iodobenzene **(514)** (0.36 mL, 3.23 mmol) gave 3,3'–oxybis(prop–1–yne–3,1–diyl)dibenzene **(519)** (0.72 g, quantitative) as a pale yellow oil after silica gel column chromatography 1:9 EtOAc/hexane. The NMR data are in agreement with the literature $^{(236)}$ and are given below for information.

(519): δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 4.56 (4H, s, 2xCH_2), 7.28–7.33 (6H, m, ArCH), 7.43–7.50 (4H, m, ArCH); δ$_c$ ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 59.0 (2xCH$_2$), 84.6 (2xCC), 87.0 (2xCC), 122.7 (4xArCH), 128.6 (2xArCH), 128.8 (4xArCH), 132.1 (2xArCH).
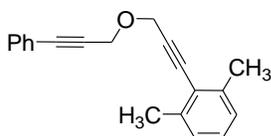
C$_{20}$H$_{18}$O
Mol. Wt.: 274.3563

1,3–Dimethyl–2–(3–(3–phenylprop–2–ynyloxy)prop–1–ynyl)benzene, **(520)**.

Using the modified literature method $^{(161)}$ in **section 5.6** (3–(prop–2–ynyloxy)prop–1–ynyl)benzene **(504)** (0.36g, 2.15 mmol) and 2–iodo–m–xylene **(515)** (0.50 mL, 2.15 mmol.) gave 1,3–dimethyl–2–(3–(3–phenylprop–2–ynyloxy)prop–1–ynyl)benzene **(520)** (0.59 g, quantitative) as a pale yellow oil after silica gel column chromatography 1:9 EtOAc/hexane.

(520): IR (thin film) v$_{max}$; 2986, 2226, 1491 and 1332 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 2.38 (6H, s, 2xCH_3), 4.52 (2H, s, CH_2), 4.58 (2H, s, CH_2), 6.96–7.27 (5H, m, ArCH), 7.38–7.42 (3H, m, ArCH); δ$_c$ ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 21.5 (2xCH_3), 57.4 (CH$_2$), 57.8 (CH$_2$), 62.4 (CC), 65.6 (CC), 84.8 (CC), 84.9 (CC), 126.5 (CAr), 127.0 (CAr), 128.6 (ArCH), 128.9 (ArCH), 129.3 (2xArCH), 132.1 (2xArCH), 137.1 (2xArCH), 140.8 (2xCAr); +ve, HRMS; NESI; m/z, calculated for C$_{20}$H$_{22}$ON; [M+NH$_4$]$^+$; requires 292.1696, found 292.1698.

Ph
C$_{19}$H$_{16}$O$_2$
Mol. Wt.: 276.3291
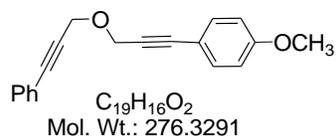
1–Methoxy–4–(3–(3–phenylprop–2–ynyloxy)prop–1–ynyl)benzene, **(521)**.

Using the modified literature method **(161)** in **section 5.6** (3–(prop–2–ynyloxy)prop–1–ynyl)benzene **(504)** (0.50 g, 2.94 mmol) and 4–iodoanisole **(516)** (0.76 mL, 3.23 mmol) gave 1–methoxy–4–(3–(3–phenylprop–2–ynyloxy)prop–1–ynyl)benzene **(521)** (0.80 g, 99%) as a pale yellow oil after silica gel column chromatography 3: 7 EtOAc/hexane.

(521): IR (thin film) v$_{max}$; 2848, 2237, 1606 and 1076 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 3.64 (3H, s, OC*H*$_3$), 4.39 (4H, s, 2xC*H*$_2$), 6.78 (2H, d, *J* 8.0 Hz, ArC*H*), 7.19 (3H, s, ArC*H*), 7.28 (2H, d, *J* 8.0 Hz, ArC*H*), 7.34–7.36 (2H, m, ArC*H*); δ$_c$ ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 55.5 (OC*H*$_3$), 57.6 (C*H*$_2$), 57.8 (C*H*$_2$), 83.2 (*CC*), 84.8 (*CC*), 87.0 (*CC*), 87.0 (*CC*), 114.2 (*C*Ar), 114.8 (*C*Ar), 122.6 (2xAr*C*H),122.8 (2xAr*C*H), 132.0 (2xAr*C*H), 133.6 (2xAr*C*H), 160.04 (Ar*C*H); +ve; HRMS; NESI; m/z, calculated for C$_{19}$H$_{17}$O$_2$; [M+H]$^+$; requires 277.1223, found 277.1225.

Ph
C$_{18}$H$_{13}$FO
Mol. Wt.: 264.2936
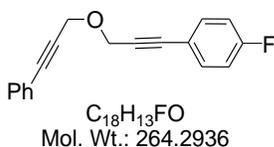
1–Fluoro–4–(3–(3–phenylprop–2–ynyloxy)prop–1–ynyl)benzene, **(522)**.

Using the modified literature method **(161)** in **section 5.6** (3–(prop–2–ynyloxy)prop–1–ynyl)benzene **(504)** (0.50 g, 2.94 mmol) and 1–fluoro 4–iodo benzene **(517)** (0.72 mL, 3.23 mmol) gave 1–fluoro–4–(3–(3–phenylprop–2–ynyloxy)prop–1–ynyl)benzene **(522)** (0.73 g, 94%) after silica gel column chromatography 3: 7 EtOAc/hexane.

(522): IR (thin film) v$_{max}$; 1457, 1351 and 1173 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 4.44 (4H, brs, C*H*$_2$), 6.69–6.93 (2H, m, ArC*H*), 7.21–7.22 (3H, m, ArC*H*), 7.32–7.37 (4H, m, ArC*H*); δ$_C$^{13}C NMR (δ, 100 MHz, CDCl$_3$); 57.6 (C*H*$_2$), 57.7 (C*H*$_2$), 84.4 (*CC*), 84.5 (*CC*), 85.9 (*CC*), 87.1 (*CC*), 115.7 (Ar*C*H), 115.9 (Ar*C*H), 118.8 (d, *J* 4.0 Hz, Ar*C*F), 122.7 (*C*Ar), 128.5 (2xAr*C*H), 128.8 (Ar*C*H), 132.0 (2xAr*C*H), 133.9 (2xAr*C*H), 161.6 (*C*Ar); δ$_F$ ^{19}F NMR (δ, 376 MHz, CDCl$_3$); –110.4; +ve; HRMS; NESP; m/z, calculated for C$_{18}$H$_{17}$OFN; [M+NH$_4$]$^+$; requires 282.1290, found 282.1289.

Me
Ph
C$_{20}$H$_{15}$F$_3$O
Mol. Wt.: 328.3277
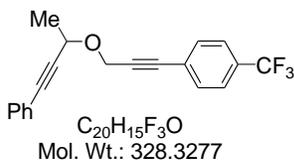
Rac–1–(3–(4–phenylbut–3–yn–2–yloxy) prop–1–ynyl)–4–(trifluoromethyl) benzene, **(523)**.

Using the modified literature method **(161)** in **section 5.6** 3–(prop–2–ynyloxy)but–1–ynyl)benzene **(502)** (0.50 g, 2.72 mmol) and 1–iodo–4–(trifluoromethyl)benzene **(518)** (0.74 mL, 2.72 mmol) gave 1–(3–(4–phenylbut–3–yn–2–

yloxy)prop–1–ynyl)–4–(trifluoromethyl)benzene **(523)** (0.85 g, 96%) as a pale yellow oil after silica gel column chromatography 1:9 EtOAc/hexane.

(523): IR (thin film) v_{max}; 2988, 1617, 1598, 842, 757 cm^{-1}; δ_H ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.52 (3H, d, *J* 4.4 Hz, C*H*$_3$), 4.57 (1H, d, *J* 13.5 Hz, C*H*$_2$), 4.75 (1H, d, *J* 13.5 Hz, C*H*$_2$), 4.60 (1H, q, *J* 4.4 Hz, C*H*), 7.22–7.29 (3H, m, ArC*H*), 7.36–7.40 (2H, m, ArC*H*), 7.46–7.52 (4H, s, ArC*H*); δ_C ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 22.1 (*C*H$_3$), 56.5 (*C*H$_2$), 65.1 (*C*H), 84.8 (*C*C), 85.9 (*C*C), 87.2 (*C*C), 88.0 (*C*C), 122.5 (*C*Ar), 126.5 (Ar*C*H), 128.0 (2xAr*C*H), 128.3 (Ar*C*H), 128.5 (Ar*C*H), 130.4 (q, *J* 16.0 Hz, Ar*C*F$_3$), 131.8 (2xAr*C*H), 132.1 (2xAr*C*H), 138.1 (*C*Ar); δ_f ^{19}F NMR (δ, 376 MHz, CDCl$_3$); –64.1; +ve; HRMS; EI; m/z, calculated for C$_{20}$H$_{14}$OF$_3$; [M–H]$^+$; requires 327.0990, found 327.0991.
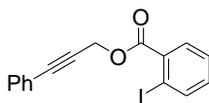
C$_{16}$H$_{11}$IO$_2$
Mol. Wt.: 362.1618

3–Phenylprop–2–ynyl 2–iodobenzoate, **(524)**.
Compound **(524)** was prepared from **(397)** (1.00 g, 7.57 mmol) using the literature method [205] and gave **(524)** (2.71 g, 99%) as a colourless oil after silica gel column chromatography using a 3:7 EtOAc/hexane.

(524): IR (thin film) v_{max}; 1718 cm^{-1}; δ_H ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 5.03, (2H, s, C*H*$_2$), 6.98 (1H, td, *J* 5.2, 1.2 Hz, ArC*H*), 7.14–7.20 (3H, m, ArC*H*), 7.23 (1H, td, *J* 5.1, 0.7 Hz, ArC*H*), 7.31–7.37 (2H, m, ArC*H*), 7.72 (1H, dd, *J* 5.2, 1.2 Hz, ArC*H*), 7.83 (1H, dd, *J* 5.1, 0.7 Hz, ArC*H*); δ_C ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 53.9 (*C*H$_2$), 82.8 (*C*C), 87.0 (*C*C), 94.4 (Ar*C*I), 122.2 (*C*Ar), 127.7 (*C*Ar), 128.5 (Ar*C*H), 128.9 (2xAr*C*H), 131.0 (Ar*C*H), 131.7 (Ar*C*H), 133.2 (2xAr*C*H), 134.3 (Ar*C*H), 141.2 (Ar*C*H), 165.6 (*C*O); +ve; HRMS; EI (NH$_3$); m/z, calculated for C$_{16}$H$_{11}$IO$_2$; [M]$^+$; requires 361.9798, found 361.9798.
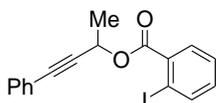
C$_{17}$H$_{13}$IO$_2$
Mol. Wt.: 376.1884

Rac–4–Phenylbut–3–yn–2–yl 2–iodobenzoate, **(525)**.
Compound **(525)** was prepared from **(391)** (1.00 g, 6.85 mmol) using the literature method [205] and gave **(524)** in 99% yield. The NMR data are in agreement with the literature [161] and are given below for information.

Rac–**(525)**: δ_H ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.72 (3H, d, *J* 6.7 Hz, C*H*$_3$), 5.93 (1H, q, *J* 6.7 Hz, C*H*), 7.14 (1H, td, *J* 7.9, 1.7 Hz, ArC*H*), 7.27–7.47 (6H, m, ArC*H*), 7.83–7.86 (1H, dd, *J* 7.7, 1.7 Hz, ArC*H*), 7.97–8.00 (1H, dd, *J* 7.9, 1.0 Hz, ArC*H*); δ_C ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 21.7 (*C*H$_3$), 62.4 (*C*H), 85.3 (*C*C), 87.3 (*C*C), 94.3 (Ar*C*I), 122.3 (*C*Ar), 128.1

(Ar*CH*), 128.4 (2xAr*CH*), 128.8 (Ar*CH*), 131.2 (2xAr*CH*), 132.0 (Ar*CH*), 132.9 (*C*Ar), 134.9 (Ar*CH*), 141.4 (Ar*CH*), 165.52 (*C*O).

$C_{18}H_{12}F_3IO_2$
Mol. Wt.: 444.1864
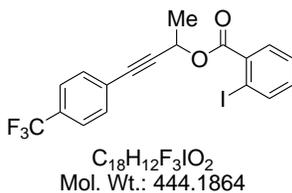
Rac–4–(4–(trifluoromethyl)phenyl)but–3–yn–2–yl 2–iodobenzoate, **(526)**.

Compound *rac*–**(526)** was prepared from 4–(4–(trifluoromethyl)phenyl)but–3–yn–2–ol **(500)** (1.00 g, 4.66 mmol) using the literature method [205] and gave **(526)** (1.90 g, 91%) as a colourless oil after silica gel column chromatography using a 1:9 CH_2Cl_2/hexane.

Rac–**(526)**: IR (thin film) v_{max}; 1732 cm^{-1}; $δ_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.67 (3H, d, *J* 6.7 Hz, C*H*$_3$), 5.84 (1H, q, *J* 6.7 Hz, C*H*), 7.09 (2H, td, *J* 7.8, 1.7 Hz, ArC*H*), 7.34 (2H, td, *J* 7.6, 1.2 Hz, ArC*H*), 7.78 (2H, dd, *J* 7.8, 1.7 Hz, ArC*H*), 7.93 (2H, dd, *J* 7.6, 1.2 Hz, ArC*H*); $δ_C$ ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 21.1 (*C*H$_3$), 62.4 (*C*H), 83.8 (*CC*), 89.6 (*CC*), 119.8 (Ar*C*I), 122.5 (Ar*C*H), 125.2 (Ar*C*H), 125.3 (Ar*C*H), 127.7 (Ar*C*H), 129.9 (Ar*C*H), 130.2 (q, *J* 33.0 Hz, Ar*C*F$_3$), 130.6 (Ar*C*H), 130.8 (Ar*C*H), 134.8 (2xAr*C*H), 141.7 (2xAr*C*H), 165.4 (*C*O); $δ_F$ ^{19}F NMR (δ, 376 MHz, CDCl$_3$); –64.1; +ve; HRMS; ESI; m/z, calculated for $C_{18}H_{16}F_3IO_2N$; [M+NH$_4$]$^+$; requires 462.0172, found 462.0169.

$C_{19}H_{17}IO_2$
Mol. Wt.: 404.2416
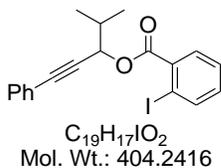
Rac–4–methyl–1–phenylpent–1–yn–3–yl 2–iodobenzoate, **(527)**.

Compound *rac*–**(525)** was prepared from 4–methyl–1–phenylpent–1–yn–3–ol **(498)** (1.63 g, 9.51 mmol) using the literature modified literature in **section 5.6** [205] and gave **(527)** in 95% yield. The NMR data are in agreement with the literature [161] and are given below for information.

Rac–**(527)**: $δ_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.03–1.11 (6H, m, (C*H*$_3$)$_2$CH), 2.10–2.22 (1H, m, C*H*), 5.61–5.65 (1H, m, C*H*), 7.03–7.09 (1H, m, ArC*H*), 7.15–7.23 (3H, m, ArC*H*), 7.29–7.38 (3H, m, ArC*H*), 7.74–7.79 (1H, t, *J* 8.0 Hz, ArC*H*), 7.88–7.93 (1H, t, *J* 8.0 Hz, ArC*H*); $δ_C$ ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 18.1 ((*C*H$_3$)$_2$CH), 18.7 ((*C*H$_3$)$_2$CH), 32.9 (*C*H), 71.1 (*C*HO), 85.1 (*CC*), 86.7 (*CC*), 94.5 (Ar*C*I), 122.6 (*C*Ar), 128.2 (Ar*C*H), 128.5 (2xAr*C*H), 128.8 (Ar*C*H), 131.4 (Ar*C*H), 132.2 (2xAr*C*H), 133.0 (Ar*C*H), 135.1 (*C*Ar), 141.7 (Ar*C*H), 165.76 (*C*O).
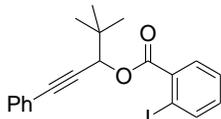
C$_{20}$H$_{19}$IO$_2$
Mol. Wt.: 418.2681

Rac–4,4–dimethyl–1–phenylpent–1–yn–3–yl 2–iodobenzoate, **(528)**.

Compound *rac*–**(528)** was prepared from 4,4'–dimethyl–1–phenylpent–1–yn–3–ol (1.00 g, 7.81 mmol) **(499)** using the literature method [205] and gave **(528)** in 95% yield. The NMR data are in agreement with the literature [202] and are given below for information.

Rac–**(528)**: δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.19 (9H, s, (CH_3)$_3$C), 5.66 (1H, s, CH), 7.09 (1H, dt, *J* 7.9, 1.7 Hz, ArCH), 7.26–7.29 (3H, m, ArCH), 7.36 (1H, t, *J* 6.5 Hz, ArCH), 7.47 (2H, m, ArCH), 7.84 (1H, dd, *J* 7.7, 1.5 Hz, ArCH) 7.95 (1H, d, *J* 7.9 Hz, ArCH); ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 26.1 (C(CH$_3$)$_3$), 35.9 (*C*(CH$_3$)$_3$), 73.8 (CH), 85.4 (*C*C), 86.5 (*C*C), 94.5 (Ar*C*I), 122.6 (*C*Ar), 128.2 (Ar*C*H), 128.5 (2xAr*C*H), 128.7 (Ar*C*H), 131.1 (Ar*C*H) 132.0 (2xAr*C*H) 132.9 (Ar*C*H), 134.9 (*C*Ar), 141.6 (Ar*C*H), 165.6 (*C*O).
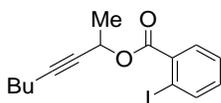
C$_{15}$H$_{17}$IO$_2$
Mol. Wt.: 356.1988

Rac–oct–3–yn–2–yl 2–iodobenzoate, **(529)**.

Compound *rac*–**(529)** was prepared from oct–3–yn–2–ol **(426)** (1.00 g, 7.99 mmol) using the literature method [205] and gave **(529)** (2.78 g, 98%) as a colourless oil after silica gel column chromatography using a 1:9 EtOAc/hexane.

Rac–**(529)**: IR (thin film) v$_{max}$; 1731 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 0.84 (3H, t, *J* 5.2 Hz, CH_3), 1.33 (2H, *sectet*, *J* 7.6 Hz, CH_2), 1.42 (2H, *quintet*, *J* 7.6 Hz, CH_2), 1.53 (3H, d, *J* 6.8 Hz, CH_3), 2.15 (2H, m, CH_2), 5.62 (1H, q, *J* 6.8 Hz, CH), 7.08 (1H, dd, *J* 8.0 Hz, ArCH), 7.33 (1H, dd, *J* 8.0 Hz, ArCH), 7.75 (1H, d, *J* 8.0 Hz, ArCH), 7.91 (1H, d, *J* 8.0 Hz, ArCH); ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 12.6 (*C*H$_3$), 17.4 (*C*H$_2$), 20.8 (*C*H$_2$), 24.4 (*C*H$_3$), 29.5 (*C*H$_2$), 61.3 (CH), 77.2 (*C*C), 85.1 (*C*C), 93.1 (Ar*C*I), 126.8 (Ar*C*H), 123.0 (Ar*C*H), 131.6 (Ar*C*H), 134.0 (*C*Ar), 140.2 (Ar*C*H), 164.5 (CO); +ve; HRMS; EI; m/z, calculated for C$_{15}$H$_{17}$IO$_2$; [M]$^+$; requires 356.0268, found 356.0267.
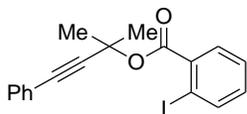
C$_{18}$H$_{15}$IO$_2$
Mol. Wt.: 390.2150

2–Methyl–4–phenylbut–3–yn–2–yl 2–iodobenzoate, **(530)**.

Compound **(530)** was prepared from 2–methyl–4–phenyl–but–3–yn **(501)** (1.00 g, 6.20 mmol) using the literature method [205] and gave **(530)** (2.30 g, 95%) as a colourless oil after silica gel column chromatography using a 3:7 EtOAc/hexane.

(530): IR (thin film) v_{max}; 1731 cm^{-1}; δ_H ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.91 (6H, s, 2xCH_3), 7.09 (1H, t, J 7.2 Hz, ArCH), 7.25–7.29 (3H, m, ArCH), 7.35 (1H, dd, J 8.0 Hz, ArCH), 7.43 (1H, dd, J 8.0 Hz, ArCH), 7.46 (1H, dd, J 8.0 Hz, ArCH), 7.74 (1H, d, J 8.0 Hz, ArCH), 7.92 (1H, d, J 8.0 Hz, ArCH); δ_C^{13}C NMR (δ, 100 MHz, CDCl$_3$); 29.4 (2xCH$_3$), 74.6 (C(CH$_3$)$_2$), 84.9 (CC), 90.0 (CC), 94.0 (ArCl), 122.8 (CAr), 128.1 (ArCH), 128.4 (2xArCH), 128.7 (ArCH), 131.0 (ArCH), 132.1 (2xArCH), 133.0 (ArCH), 136.5 (CAr), 141.3 (ArCH), 165.3 (CO); +ve; HRMS; pEI; m/z, calculated for C$_{18}$H$_{15}$O$_2$I; [M]$^+$; requires 390.0108, found 390.0111.

C$_{24}$H$_{16}$O$_2$
Mol. Wt.: 336.3826
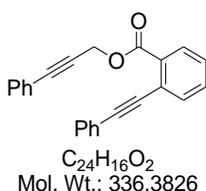
3–Phenylprop–2–ynyl 2–(phenylethynyl)benzoate, **(533)**.

Using the modified literature method [161] in **section 5.6**, 3–phenylprop–2–ynyl 2–iodobenzoate **(524)** (1.00 g, 5.51 mmol) and phenylacetylene (0.57 mL, 5.51 mmol) gave **(533)** (1.83 g, 98%) as a white powder after silica gel column chromatography with 1:10 EtOAc/petroleum ether 40–60°C.

(533): m.p. 78–80°C; Anal Calc. for C$_{24}$H$_{16}$O$_2$, Calc; C, 85.69; H, 4.79, Found; C, 85.72; H, 4.74; IR (thin film) v_{max}; 1717 cm^{-1}; δ_H ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 5.12 (2H, s, CH_2), 7.15–7.24 (6H, m, ArCH), 7.28–7.35 (3H, m, ArCH), 7.42 (1H, td, J 2.7, 0.9 Hz, ArCH), 7.51 (1H, d, J 2.8 Hz, ArCH), 7.52 (1H, d, J 2.8 Hz, ArCH), 7.57 (1H, dd, J 5.3, 0.7 Hz, ArCH), 7.96 (1H, dd, J 5.3, 0.7 Hz, ArCH); δ_C ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 53.6 (CH$_2$), 83.3 (CC), 86.9 (CC), 88.3 (CC), 94.9 (CC), 122.3 (CAr), 123.4 (CAr), 124.3 (CAr), 128.0 (ArCH), 128.4 (4xArCH), 128.6 (ArCH), 128.9 (ArCH), 130.9 (ArCH), 131.2 (CAr), 131.9 (2xArCH), 132.1 (2xArCH), 132.2 (ArCH), 134.5 (ArCH), 165.6 (CO); +ve; HRMS; ESI; m/z, calculated for C$_{24}$H$_{20}$O$_2$N; [M+NH$_4$]$^+$; requires 354.1489, found 354.1486.

C$_{25}$H$_{15}$F$_3$O$_2$
Mol. Wt.: 404.3806
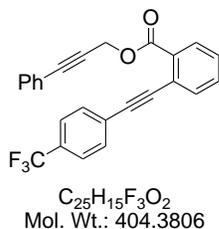
3–Phenylprop–2–ynyl 2–((4–(trifluoromethyl)phenyl)ethynyl)benzoate, **(534)**.

Using the modified literature method [161] in **section 5.6**, 3–phenylprop–2–ynyl 2–iodobenzoate **(524)** (2.00 g, 5.51 mmol) and 1–ethynyl–4–(trifluoromethyl)benzene (0.97 mL, 5.51 mmol) gave **(534)** (2.10 g, 94%) as a white powder after silica gel column chromatography with 1:9 EtOAc/petroleum ether 40–60°C.

(534): m.p. 54–56°C; Anal. Calc. for $C_{25}H_{15}F_3O_2$; Calc.; C, 74.25; H, 3.74; Found C, 74.19; H, 3.67; IR (thin film) v_{max}; 3065, 2935, 2232, 2118, 1718, 1490 and 1318 cm^{-1}; δ_H ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 5.24 (2H, s, CH_2), 7.29–7.38 (3H, m, ArCH), 7.41–7.44 (2H, m, ArCH), 7.45–7.52 (3H, m, ArCH), 7.57 (1H, td, J 5.1, 0.9 Hz, ArCH), 7.70–7.74 (3H, m, ArCH), 8.15 (1H, dd, J 5.3, 0.7 Hz, ArCH); δ_C ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 53.7 (*C*H$_2$), 83.0 (*CC*), 87.0 (*CC*), 90.4 (*CC*), 93.1 (*CC*), 122.2 (*C*Ar), 123.3 (*C*Ar), 125.3 (Ar*C*H), 127.1 (*C*Ar), 128.3 (4xAr*C*H), 128.9 (Ar*C*H), 129.9 (*C*Ar), 130.0 (q, J 14.0 Hz, Ar*C*F$_3$), 131.4 (*C*Ar), 131.9 (Ar*C*H), 131.4 (Ar*C*H), 132.0 (Ar*C*H), 132.1 (Ar*C*H), 132.3 (2xAr*C*H), 134.2 (Ar*C*H), 165.5 (*C*O); δ_F ^{19}F NMR (δ, 376 MHz, CDCl$_3$); –63.9; +ve; HRMS; ESI; m/z, calculated for $C_{25}H_{19}F_3O_2N$; [M+NH$_4$]$^+$; requires 422.1362, found 422.1366.

$C_{26}H_{17}F_3O_2$
Mol. Wt.: 418.4072
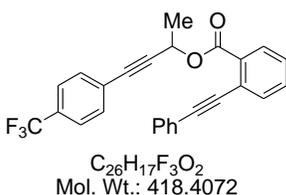
Rac–4–(4–(trifluoromethyl)phenyl)but–3–yn–2–yl 2–(phenylethynyl) benzoate, **(535)**.

Using the modified literature method [161] in **section 5.6**, 4–(4–(trifluoromethyl)phenyl)but–3–yn–2–yl 2–iodobenzoate **(526)** (0.50 g, 1.12 mmol) and phenyl acetylene (0.13 mL, 1.12 mmol) gave **(535)** (0.45 g, 96%) as a colourless oil after silica gel column chromatography with 1:9 EtOAc/petroleum ether 40–60°C.

Rac–**(535)**: m.p. 38–40°C; Anal. Calc. for $C_{26}H_{17}F_3O_2$; Calc.; C, 74.63; H, 4.10; Found; C, 74.71; H, 4.13; IR (thin film) v_{max}; 1724 cm^{-1}; δ_H ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.67 (3H, d, J 8.1 Hz, CH_3), 5.91 (1H, q, J 8.1 Hz, CH), 7.20–7.25 (3H, m, ArCH), 7.32 (1H, td, J 5.2, 0.8 Hz, ArCH), 7.38–7.47 (5H, m, ArCH), 7.49–7.53 (2H, m, ArCH), 7.59 (1H, dd, J 5.2 , 0.6 Hz, ArCH), 7.95 (1H, dd, J 5.2, 0.6 Hz, ArCH); δ_C ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 21.5 (*C*H$_3$), 61.5 (*C*H), 83.5 (*CC*), 88.1 (*CC*), 90.0 (*CC*), 94.6 (*CC*), 123.3 (*C*Ar), 123.9 (*C*Ar), 125.2 (q, J 4.0 Hz, Ar*C*F$_3$), 126.2 (*C*Ar), 128.0 (Ar*C*H), 128.3 (2xAr*C*H), 128.5 (Ar*C*H), 129.8 (*C*Ar), 130.1 (Ar*C*H), 130.7 (Ar*C*H), 131.6 (Ar*C*H), 131.7 (2xAr*C*H), 131.9 (Ar*C*H), 132.1 (2xAr*C*H), 134.1 (Ar*C*H), 165.3 (*C*O); δ_F ^{19}F NMR (δ, 376 MHz, CDCl$_3$); –64.0; +ve; HRMS; pEI; m/z, calculated for $C_{26}H_{17}F_3O_2$; [M]$^+$; requires 418.1175, found 418.1173.
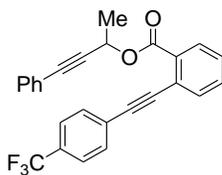
C$_{26}$H$_{17}$F$_3$O$_2$
Mol. Wt.: 418.4072

Rac–4–phenylbut–3–yn–2–yl 2–((4–(trifluoromethyl)phenyl)ethynyl) benzoate, **(536)**.

Using the modified literature method [161] in **section 5.6**, 4–phenylbut–3–yn–2–yl 2–iodobenzoate (0.25 g, 0.66 mmol) and 1–ethynyl–4–(trifluoromethyl)benzene (0.10 mL, 0.66 mmol) gave *rac*–**(536)** (0.26 g, 93%) as a colourless oil after silica gel column chromatography with 1:9 EtOAc/petroleum ether 40–60°C.

Rac–**(536)**: IR (thin film) v_{max}; 1732 cm^{-1}; δ_H ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.72 (3H, d, *J* 6.7 Hz, C*H*$_3$), 5.60 (1H, q, *J* 6.7 Hz, C*H*), 7.23–7–7.32 (4H, m, ArC*H*), 7.36–7.56 (6H, m, ArC*H*), 7.65–7.70 (2H, m, ArC*H*), 8.05 (1H, dd, *J* 7.6, 1.2 Hz, ArC*H*); δ_C^{13}C NMR (δ, 67 MHz, CDCl$_3$); 21.8 (*C*H$_3$), 62.0 (*C*H), 85.1 (*CC*), 87.5 (*CC*), 90.5 (*CC*), 93.0 (*CC*), 122.3 (*C*Ar), 123.2 (*C*Ar), 125.3 (q, *J* 4.0 Hz, Ar*C*F$_3$), 126.0 (*C*Ar), 127.2 (*C*Ar), 128.3 (2xAr*C*H), 128.6 (Ar*C*H), 128.8 (Ar*C*H), 128.9 (*C*Ar), 130.9 (Ar*C*H), 131.9 (2xAr*C*H), 132.0 (4xAr*C*H), 134.2 (Ar*C*H), 141.4 (Ar*C*H), 165.2 (*C*O); δ_F ^{19}F NMR (δ, 376 MHz, CDCl$_3$); –63.8; +ve; HRMS; ESI; m/z, calculated for C$_{26}$H$_{21}$F$_3$O$_2$N; [M+NH$_4$]$^+$; requires 436.1518, found 436.1519.
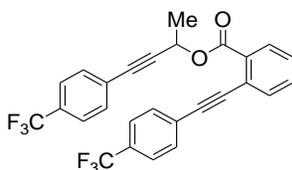
C$_{27}$H$_{16}$F$_6$O$_2$
Mol. Wt.: 486.4052

Rac–4–(4–(trifluoromethyl)phenyl)but–3–yn–2–yl 2–((4–(trifluoromethyl)phenyl) ethynyl) benzoate, **(537)**.

Using the modified literature method [161] in **section 5.6**, *rac*–4–(4–(trifluoromethyl)phenyl)but–3–yn–2–yl 2–iodobenzoate **(526)** (1.00 g, 2.25 mmol) and 1–ethynyl–4–(trifluoromethyl)benzene (0.39 mL, 2.25 mmol) gave *rac*–**(537)** (1.01 g, 94%) as a colourless oil after silica gel column chromatography with 1:9 EtOAc/petroleum ether 40–60°C.

Rac–**(537)**: m.p. 40–42°C; Anal. Calc. for C$_{27}$H$_{16}$F$_6$O$_2$; Calc.; C, 66.67; H, 3.32; Found; C, 66.72; H, 3.28; IR (thin film) v_{max}; 1709 cm^{-1}; δ_H ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.64 (3H, d, *J* 8.1 Hz, C*H*$_3$), 5.91 (1H, q, *J* 8.1 Hz, C*H*), 7.34–7.40 (3H, d, *J* 9.5 Hz, ArC*H*), 7.42–7.49 (5H, d, *J* 6.8 Hz, ArC*H*), 7.58–7.63 (3H, d, *J* 9.5 Hz, ArC*H*), 7.99 (1H, d, *J* 5.4 Hz, ArC*H*); δ_C^{13}C NMR (δ, 100 MHz, CDCl$_3$); 21.5 (*C*H$_3$), 62.0 (*C*H), 83.6 (*CC*), 89.9 (*CC*), 90.4 (*CC*), 92.9 (*CC*), 122.5 (2x*C*Ar), 123.2 (Ar), 125.2 (q, *J* 4.0 Hz, 2xAr*C*F$_3$), 126.1 (Ar), 126.8 (Ar), 127.1 (Ar*C*H), 128.5 (Ar*C*H), 130.3 (2x*C*Ar), 130.8 (Ar*C*H),131.6 (*C*Ar), 131.9 (2xAr*C*H), 132.1 (3xAr*C*H), 134.2 (Ar*C*H), 165.0 (*C*O); δ_F ^{19}F NMR (δ, 376 MHz,

CDCl$_3$); –63.4, –64.0; +ve; HRMS; ESI; m/z, calculated for C$_{27}$H$_{20}$F$_6$O$_2$N; [M+NH$_4$]$^+$; requires 504.1393, found 504.1394.

C$_{28}$H$_{24}$O$_2$
Mol. Wt.: 392.4890
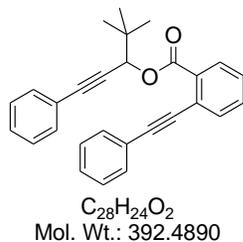
Rac–4,4–dimethyl–1–phenylpent–1–yn–3–yl 2–(phenylethynyl) benzoate, **(538)**.

Using the modified literature method $^{(161)}$ in **section 5.6**, *rac*–4,4–dimethyl–1–phenylpent–1–yn–3–yl 2–iodobenzoate **(528)** (1.00 g, 2.37 mmol) and phenylacetylene (0.24 mL, 2.37 mmol) gave *rac*–**(538)** (0.93 g, quantitative) as a colourless oil after silica gel column chromatography with 1:9 EtOAc/petroleum ether 40–60°C. The NMR data are in agreement with the literature $^{(202)}$ and are given below for information.

Rac–**(538)**: δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.20 (9H, s, (C*H*$_3$)$_3$C), 5.74 (1H, s, C*H*O), 7.16–7.24 (6H, m, ArC*H*), 7.27–7.37 (3H, m, ArC*H*), 7.39 (1H, td, *J* 7.6, 1.6 Hz, ArC*H*), 7.50 (1H, d, *J* 2.8 Hz, ArC*H*), 7.52 (1H, d, *J* 1.6 Hz, ArC*H*), 7.58 (1H, dd, *J* 8.4, 0.4 Hz, ArC*H*), 7.95 (1H, dd, *J* 8.4, 0.4 Hz, ArC*H*); δ$_C$ ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 26.1 ((*C*H$_3$)$_3$C), 36.1 (*C*(CH$_3$)$_3$), 73.3 (H*C*), 85.9 (*CC*), 86.1 (*CC*), 88.5 (*CC*), 94.9 (*CC*), 122.8 (*C*Ar), 123.6 (*C*Ar), 124.3 (*C*Ar), 128.1 (Ar*C*H), 128.4 (2xAr*C*H), 128.5 (2xAr*C*H), 128.7 (2xAr*C*H), 130.8 (Ar*C*H), 131.9 (*C*Ar), 132.0 (Ar*C*H), 132.1 (4xAr*C*H), 134.5 (Ar*C*H), 165.5 (*C*O).

C$_{23}$H$_{22}$O$_2$
Mol. Wt.: 330.4196
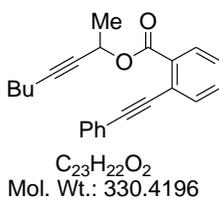
Rac–oct–3–yn–2–yl 2–(phenylethynyl)benzoate, **(539)**.

Using the modified literature method $^{(161)}$ in **section 5.6**, oct–3–yn–2–yl 2–iodobenzoate **(529)** (1.00 g, 2.81 mmol) and phenylacetylene (0.29 mL, 2.81 mmol) gave **(539)** as a colourless oil (0.92 g, 97%) after silica gel column chromatography using 1:9 EtOAc/petroleum ether 40–60°C.

Rac–**(539)**: IR (thin film) v$_{max}$; 1731 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 0.80 (3H, t, *J* 7.2 Hz, C*H*$_3$), 1.31 (2H, *sextet*, *J* 7.6 Hz, C*H*$_2$), 1.38 (2H, *quintet*, *J* 7.6 Hz, C*H*$_2$), 1.53 (3H, d, *J* 6.4 Hz, C*H*$_3$), 2.10 (2H, dt, *J* 6.8, 1.6 Hz, C*H*$_2$), 5.67 (1H, q, *J* 6.4 Hz, C*H*), 7.27–7.29 (3H, m, ArC*H*), 7.32 (1H , d, *J* 7.60 Hz, ArC*H*), 7.42 (1H, td, *J* 7.6, 0.8 Hz, ArC*H*), 7.53 (1H, d, *J* 2.0 Hz, ArC*H*), 7.54 (1H, d, *J* 4.0 Hz, ArC*H*), 7.57 (1H, d, *J* 7.6 Hz, ArC*H*), 7.92 (1H, d, *J* 7.6 Hz, ArC*H*); δ$_C$ ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 13.8 (*C*H$_3$), 18.6 (*C*H$_2$), 22.1 (*C*H$_2$), 22.2 (*C*H$_3$), 30.7 (*C*H$_2$), 62.1 (*C*H), 79.0 (*CC*), 86.1 (*CC*), 88.5 (*CC*), 94.6 (*CC*), 123.6 (*C*Ar), 123.9 (*C*Ar), 128.1 (Ar*C*H), 128.5 (2xAr*C*H), 128.7 (Ar*C*H), 130.9 (Ar*C*H), 131.9

(3xAr*CH*), 132.1 (*C*Ar) 134.3 (Ar*CH*), 165.5 (*CO*); +ve; HRMS; pEI; m/z, calculated for $C_{23}H_{22}O_2$; [M]$^+$; requires 330.1618, found 330.1614.

$C_{26}H_{20}O_2$
Mol. Wt.: 364.4358
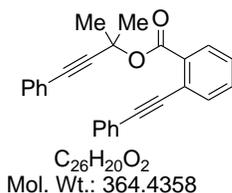
2–Methyl–4–phenyl but–3–yn–2–yl 2–(phenylethynyl)benzoate, **(540)**.

Using the modified literature method [161] in **section 5.6**, 2–methyl–4–phenylbut–3–yn–2–yl 2–iodobenzoate (1.00 g, 2.56 mmol) and phenyl acetylene (0.27 mL, 2.56 mmol) gave **(540)** as a colourless oil (0.89 g, 96%) after silica gel column chromatography using 3:7 EtOAc/hexane.

(540): IR (thin film) v$_{max}$; 1728 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.81 (6H, s, 2x C*H$_3$*), 7.12–7.21 (6H, m, Ar*CH*), 7.28 (1H, td, *J* 6.4, 4.0 Hz, Ar*CH*), 7.30–7.38 (3H, m, Ar*CH*), 7.44–7.48 (2H, m, Ar*CH*), 7.53 (1H, d, *J* 8.0 Hz, Ar*CH*), 7.82 (1H, d, *J* 8.0 Hz, Ar*CH*); δ$_C$ ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 29.3 (2xCH$_3$), 73.8 (*C*(CH$_3$)), 84.7 (*CC*), 88.5 (*CC*), 90.5 (*CC*), 94.3 (*CC*), 122.9 (*C*Ar), 123.5 (*C*Ar), 123.6 (*C*Ar), 128.2 (Ar*CH*), 128.4 (2xAr*CH*), 128.5 (3xAr*CH*), 128.6 (Ar*CH*), 130.5 (Ar*CH*), 131.6 (Ar*CH*), 131.9 (2xAr*CH*), 132.0 (2xAr*CH*), 133.5 (*C*Ar), 134.1 (Ar*CH*), 165.2 (*CO*); +ve; HRMS; pEI; m/z, calculated for $C_{26}H_{20}O_2$; [M]$^+$; requires 364.1458, found 364.1462.

$C_{22}H_{22}O_2Si$
Mol. Wt.: 346.4944
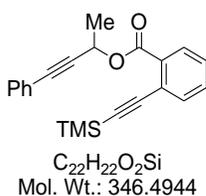
Rac–4–phenylbut–3–yn–2–yl 2–((trimethylsilyl)ethynyl)benzoate, **(541)**.

Using the modified literature method [161] in **section 5.6**, 4–phenylbut–3–yn–2–yl 2–iodobenzoate **(525)** (0.50 g, 1.33 mmol) and trimethylsilyl acetylene (0.20 mL, 2.00 mmol) gave **(541)** as a colourless oil (0.42 g, 92%) after silica gel column chromatography using 1:9 EtOAc/ petroleum ether 40–60°C.

Rac–**(541)**: IR (thin film) v$_{max}$; 1733 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 0.29 (9H, s, Si(C*H$_3$*)$_3$), 1.72 (3H, d, *J* 6.7 Hz, C*H$_3$*CH), 5.96 (1H, q, *J* 6.7 Hz, CH$_3$C*H*), 7.08 (1H, t, *J* 7.9 Hz, Ar*CH*), 7.26–7.47 (6H, m, Ar*CH*), 7.81 (1H, d, *J* 7.6 Hz, Ar*CH*), 7.93 (1H, d, *J* 7.9 Hz, Ar*CH*); δ$_C$ ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 0.00 (Si(CH$_3$)$_3$), 21.7 (*C*H$_3$), 61.8 (*CH*), 84.9 (*CC*), 87.6 (*CC*), 100.1 (*CC*), 103.3 (*CC*), 122.4 (*C*Ar), 123.5 (*C*Ar), 128.2 (2xAr*CH*), 128.3 (2xAr*CH*), 128.7 (Ar*CH*), 130.5 (Ar*CH*), 131.7 (Ar*CH*), 132.0 (Ar*CH*), 132.1 (*C*Ar), 134.9 (Ar*CH*), 165.3 (*CO*); +ve; HRMS; pCI; m/z, calculated for $C_{22}H_{26}O_2SiN$; [M+NH$_4$]$^+$; requires 364.1722, found 364.1727.
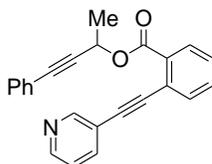
C$_{24}$H$_{17}$NO$_2$
Mol. Wt.: 351.3973

Rac–4–phenylbut–3–yn–2–yl 2–(pyridin–3–ylethynyl)benzoate, **(542)**.

Using the modified literature method [161] in **section 5.6** 4–phenylbut–3–yn–2–yl 2–iodobenzoate **(525)** (1.83 g, 4.85 mmol) and 3–iodopyridine (0.57 mL, 5.34 mmol) gave **(542)** (1.67 g, 98%) as a pale yellow oil after silica gel column chromatography with 1:9 EtOAc/petroleum ether 40–60°C.

Rac–**(542)**: IR (thin film) v_{max}; 1727 cm^{-1}; δ_H ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.60 (3H, d, *J* 6.8 Hz, C*H*$_3$), 5.87 (1H, q, *J* 6.8 Hz, C*H*), 7.04 (1H, dd, *J* 5.2 Hz, ArC*H*), 7.11–7.19 (3H, m, ArC*H*), 7.25–7.30 (3H, m, ArC*H*), 7.38 (1H, t, *J* 7.6 Hz, ArC*H*), 7.53 (1H, d, *J* 7.6 Hz, ArC*H*), 7.74 (1H, d, *J* 8.0 Hz, ArC*H*), 7.92 (1H, d, *J* 7.6 Hz, ArC*H*), 8.38 (1H, d, *J* 4.4 Hz, ArC*H*), 8.73 (1H, s, ArC*H*); δ_C^{13}C NMR (δ, 100 MHz, CDCl$_3$); 21.9 (*C*H$_3$), 62.0 (*C*H), 85.2 (*C*C), 87.6 (*C*C), 91.1 (*C*C), 91.6 (*C*C), 120.7 (*C*Ar), 122.3 (*C*Ar), 123.2 (Ar*C*H), 123.3 (*C*Ar), 128.5 (2xAr*C*H), 128.7 (Ar*C*H), 128.8 (Ar*C*H), 131.0 (Ar*C*H), 131.8 (*C*Ar), 132.0 (2xAr*C*H), 132.2 (Ar*C*H), 134.3 (Ar*C*H), 138.8 (Ar*C*H), 148.9 (Ar*C*H), 152.4 (Ar*C*H), 165.1 (*C*O); +ve; HRMS; ESI; m/z, calculated for C$_{24}$H$_{18}$NO$_2$; [M+H]$^+$; requires 352.1332, found 352.1330.
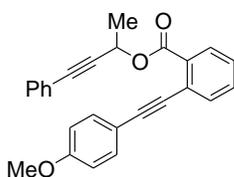
C$_{26}$H$_{20}$O$_3$
Mol. Wt.: 380.4352

Rac–4–phenylbut–3–yn–2–yl 2–((4–methoxyphenyl)ethynyl)benzoate, **(543)**.

Using the modified literature method [161] in **section 5.6** 4–phenylbut–3–yn–2–yl 2–iodobenzoate **(525)** (1.43 g, 3.79 mmol) and 4–methoxy iodobenzene (0.97 g, 4.16 mmol) gave *rac*–**(543)** (1.44 g, 95%) as a colourless oil after silica gel column chromatography with 1:20 EtOAc/petroleum ether 40–60°C.

Rac–**(543)**: IR (thin film) v_{max}; 1728 cm^{-1}; δ_H ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.65 (3H, d, *J* 6.8 Hz, C*H*$_3$), 3.73 (3H, s, OC*H*$_3$), 5.92 (1H, q, *J* 6.8 Hz, C*H*), 6.73 (2H, m, ArC*H*), 7.18–7.48 (9H, m, ArC*H*), 7.56 (1H, d, *J* 8.0 Hz, ArC*H*), 7.94 (1H,d, *J* 8.0 Hz, ArC*H*); δ_C ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 22.0 (*C*H$_3$), 55.4 (O*C*H$_3$), 61.9 (*C*H), 85.2 (*C*C), 87.4 (*C*C), 88.0 (*C*C), 95.1 (*C*C), 114.2 (2xAr*C*H), 114.4 (Ar*C*H), 115.6 (Ar*C*H), 122.5 (*C*Ar), 124.4 (*C*Ar), 127.8 (Ar*C*H), 128.5 (2xAr*C*H), 128.9 (Ar*C*H), 130.9 (Ar*C*H), 132.1 (2xAr*C*H), 133.6 (2xAr*C*H), 134.2 (*C*Ar), 134.3 (*C*Ar), 160.1 (*C*ArOMe), 165.6 (*C*O); +ve; HRMS; pEI; m/z, calculated for C$_{26}$H$_{20}$O$_3$; [M]$^+$; requires 380.1407, found 380.1404.
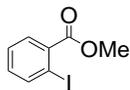
C₈H₇IO₂
Mol. Wt.: 262.0445

2–Iodomethyl benzoate, **(544)**.

Compound 2–iodomethyl benzoate **(544)** was synthesised from 2–iodobenzoic acid (1.01 g, 4.44 mmol) using the literature method [237] in 81% yield. The NMR data are in agreement with the literature [238] and are given below for information.

(544): δ_H ^{1}H NMR (δ, 400 MHz, CDCl₃); 3.77 (3H, s, OCH_3), 7.69 (1H, t, *J* 8.0, ArC*H*), 7.42 (1H, t, *J* 8.0 Hz, ArC*H*), 7.81 (1H, d, *J* 8.0, ArC*H*), 7.99 (1H, d, *J* 8.0 Hz, ArC*H*); δ_C ^{13}C NMR (δ, 100 MHz, CDCl₃); 52.0 (OCH_3), 94.0 (*C*I), 128.0 (Ar*C*H), 130.9 (Ar*C*H), 132.1 (Ar*C*H), 135.0 (Ar*C*H), 142.0 (*C*Ar),167.0 (*C*O).
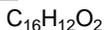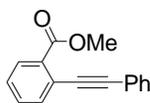
C₁₆H₁₂O₂
Mol. Wt.: 236.2653

Methyl 2–(phenylethynyl)benzoate, **(545)**.

Using the modified literature method [161] in **section 5.6**, 2–iodomethyl benzoate **(544)** (1.00 g, 3.82 mmol) and phenylacetylene (0.58 mL, 5.72 mmol) gave **(545)** in (1.34 g, 98%) as a white solid. The NMR data are in agreement with the literature [239] and are given below for information.

(545): δ_H ^{1}H NMR (δ, 400 MHz, CDCl₃); 3.98 (3H, s, CH_3), 7.30–7.35 (5H, m, ArC*H*), 7.44 (1H, td, *J* 8.0, 1.2 Hz, ArC*H*), 7.59 (2H, m, ArC*H*), 7.61 (1H, dd, *J* 8.0, 1.2 Hz, ArC*H*), 7.94 (1H, dd, *J* 8.0, 1.2 Hz, ArC*H*); δ_C^{13}C NMR (δ, 100 MHz, CDCl₃) 52.1 (OCH_3), 88.0 (*C*C), 94.0 (*C*C), 124.0 (2x*C*Ar), 128.0 (*C*Ar), 128.1 (3xAr*C*H), 130.5 (2xAr*C*H), 132.0 (3xAr*C*H), 134.0 (Ar*C*H), 167.0 (*C*O).
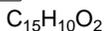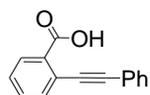
C₁₅H₁₀O₂
Mol. Wt.: 222.2387

(456).

2–(Phenylethynyl)benzoic acid **(456)** was synthesised from methyl 2–(phenylethynyl)benzoate **(545)** (1.00 g, 4.20 mmol) using the literature method [240] and gave **(456)** in 60% yield. The NMR data are in agreement with the literature and are given below for information.

(456): δ_H ^{1}H NMR (δ, 400 MHz, CDCl₃); 7.05–7.10 (4H, m, ArC*H*), 7.10–7.15 (1H, brs, ArC*H*), 7.40–7.50 (2H, brs, ArC*H*), 7.60 (1H, brs, ArC*H*), 8.0–8.05 (1H, brs, ArC*H*), 11.30 (1H, brs, O*H*); δ_C ^{13}C NMR (δ, 100 MHz, CDCl₃); 88.0

(*CC*), 96.0 (*CC*), 124.0 (*C*Ar), 125.0 (*C*Ar), 128.0 (Ar*C*H), 128.1 (2xAr*C*H), 128.2 (Ar*C*H), 130.0 (Ar*C*H), 131.0 (2xAr*C*H), 132.0 (Ar*C*H), 132.1 (Ar*C*H), 134.0 (*C*Ar), 172.0 (*C*O).
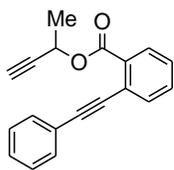
C$_{19}$H$_{14}$O$_2$
Mol. Wt.: 274.3133

Rac–but–3–yn–2–yl 2–(phenylethynyl)benzoate, **(547)**.

Compound *Rac*–**(547)** was prepared from 2–(phenylethynyl)benzoic acid **(545)** (2.00 g, 9.00 mmol) and *Rac*–but–3–yn–2–ol **(104)** (0.86 mL, 9.00 mmol) using the literature method **(205)** to give **(547)** (2.32 g, 94%) as a colourless oil after silica gel column chromatography using 1:9 EtOAc/petroleum ether 40–60°C.

Rac–**(547)**: m.p. 40–42°C; IR (thin film) v$_{max}$; 1732 cm^{-1}; Anal. Calc. for C$_{19}$H$_{14}$O$_2$; Calc.; C, 83.19, H, 5.14; Found; C, 83.17, H, 5.14; δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 1.64 (3H, d, *J* 6.7 Hz, C*H$_3$*), 5.91 (1H, q, *J* 6.7 Hz, C*H*), 7.15–7.33 (4H, m, ArC*H*), 7.39–7.45 (1H, td, *J* 7.4, 1.2 Hz, ArC*H*), 7.50–7.59 (4H, m, ArC*H*), 7.93–7.96 (1H, dd, *J* 7.9, 1.0 Hz, ArC*H*); δ$_C$^{13}C NMR (δ, 100 MHz, CDCl$_3$); 21.6 (*C*H$_3$), 61.1 (*C*H), 73.8 (*C*C), 82.5 (*C*C), 88.5 (*C*C), 94.9 (*C*C), 123.5 (*C*Ar), 124.1 (*C*Ar), 128.2 (Ar*C*H), 128.6 (2xAr*C*H), 128.9 (Ar*C*H), 130.9 (Ar*C*H), 131.5 (*C*Ar), 132.0 (2xAr*C*H), 132.3 (Ar*C*H), 134.4 (Ar*C*H), 165.2 (*C*O); +ve; HRMS; ESI; m/z, calculated for C$_{19}$H$_{15}$O$_2$; [M+H]$^+$; requires 275.1065, found 275.1067.
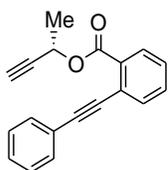
C$_{19}$H$_{14}$O$_2$
Mol. Wt.:274.3133

(*S*)–(–)–But–3–yn–2–yl 2–(phenylethynyl)benzoate, **(547)**.

Compound (*S*)–(–)–**(547)** was prepared from 2–(phenylethynyl)benzoic acid **(545)** (3.16 g, 14.26 mmol) and (*S*)–(–)–3–butyn–2–ol **(104)** (0.86 mL, 9.00 mmol) using the literature method **(205)** to give (*S*)–(–)–**(547)** (3.91 g, 96%).

(*S*)–(–)–**(547)**: m.p. 42–44°C; [α]$_D$ = –47.5 (*c* 1.10, 25.0°C , CHCl$_3$); ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.61 (3H, d, *J* 6.8 Hz, C*H$_3$*), 2.48 (1H, s, C*H*), 5.71 (1H, q, *J* 6.8 Hz, C*H*), 7.26–7.36 (3H, m, ArC*H*), 7.42–7.48 (1H, td, *J* 7.4, 1.2 Hz, ArC*H*), 7.52–7.64 (4H, m, ArC*H*), 7.94–7.99 (1H, d, *J* 7.9 Hz, ArC*H*); δ$_C$^{13}C NMR (δ, 100 MHz, CDCl$_3$); 21.6 (*C*H$_3$), 61.1 (*C*H), 73.6 (*C*C), 82.4 (*C*C), 88.4 (*C*C), 94.9 (*C*C), 123.5 (*C*Ar), 124.1 (*C*Ar), 128.2 (Ar*C*H), 128.6 (2xAr*C*H), 128.8 (Ar*C*H), 130.9 (Ar*C*H), 131.5 (*C*Ar), 132.0 (2xAr*C*H), 132.2 (Ar*C*H), 134.4 (Ar*C*H), 165.2 (*C*O); +ve; HRMS; NESI; m/z, calculated for C$_{19}$H$_{18}$O$_2$N; [M+NH$_4$]$^+$; requires 292.1332, found 292.1329; HPLC (CHIRALCEL OD) 96.5:3.5 hexane/isopropyl alcohol, 1 mL/min R$_t$=8 min 48 secs (*S*–enantiomer), R$_t$= 7 min 18 secs (*R*–enantiomer).
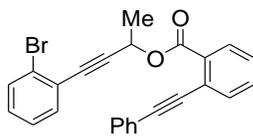
C$_{25}$H$_{17}$BrO$_2$
Mol. Wt.: 429.3053

Rac–4–(2–bromophenyl)but–3–yn–2–yl 2–(phenylethynyl)benzoate, **(548)**.

Using the modified literature method [161] in **section 5.6** but–3–yn–2–yl 2–(phenylethynyl)benzoate **(547)** (0.50 g, 1.77 mmol) and 1–bromo–2–iodo–benzene (0.25 mL, 1.94 mmol) gave *rac*–**(548)** (0.75 g, 99%) as a pale yellow oil after silica gel column chromatography using 3:7 EtOAc/petroleum ether 40–60°C.

Rac–**(548)**: IR (thin film) ν$_{max}$; 1732, 550 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.68 (3H, d, *J* 6.8 Hz, C*H*$_3$), 5.94 (1H, q, *J* 6.8 Hz, C*H*), 7.08 (1H, td, *J* 7.6, 1.6 Hz, ArC*H*), 7.14 (1H, td, *J* 7.6, 1.2 Hz, ArC*H*), 7.19–7.25 (3H, m, ArC*H*), 7.31–7.35 (2H, m, ArC*H*), 7.44 (1H, td, *J* 7.6, 1.2 Hz, ArC*H*), 7.49 (1H, dd, *J* 8.0, 1.2 Hz, ArC*H*), 7.52–7.54 (2H, m, ArC*H*), 7.59 (1H, dd, *J* 7.6, 1.2 Hz, ArC*H*), 7.96 (1H, dd, *J* 8.0, 1.2 Hz, ArC*H*); δ$_C$ ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 21.8 (*C*H$_3$), 61.9 (*C*H), 83.7 (*C*C), 88.4 (*C*C), 92.4 (*C*C), 94.9 (*C*C), 123.5 (*C*Ar), 124.1 (*C*Ar), 124.6 (*C*Ar), 126.0 (*C*Ar), 127.2 (Ar*C*H), 128.2 (Ar*C*H), 128.6 (2xAr*C*H), 128.7 (Ar*C*H), 130.0 (Ar*C*H), 131.0 (Ar*C*H), 131.8 (*C*Ar), 132.0 (2xAr*C*H), 132.1 (Ar*C*H), 132.6 (Ar*C*H), 133.8 (Ar*C*H), 134.3 (Ar*C*H), 165.5 (*C*O); +ve; HRMS; pEI; m/z, calculated for C$_{25}$H$_{17}$^{79}BrO$_2$; [M]$^+$; requires 428.0406, found 428.0404.
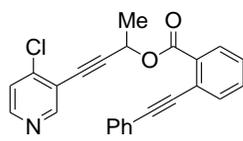
C$_{24}$H$_{16}$ClNO$_2$
Mol. Wt.: 385.8423

Rac–4–(4–chloropyridin–3–yl)but–3–yn–2–yl 2–(phenylethynyl)benzoate, **(549)**.

Using the modified literature method [161] in **section 5.6** but–3–yn–2–yl 2–(phenylethynyl)benzoate **(547)** (0.63 g, 2.24 mmol) and 4–chloro–3–iodo–pyridine (0.30 mL, 2.46 mmol) gave *rac*–**(549)** (0.86 g, 99%) as a pale yellow oil after silica gel column chromatography using 1:9 EtOAc/petroleum ether 40–60°C

(549): IR (thin film) ν$_{max}$; 1731 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.69 (3H, d, *J* 6.8 Hz, C*H*$_3$), 5.95 (1H, q, *J* 6.8 Hz, C*H*), 7.19–7.25 (4H, m, ArC*H*), 7.31–7.36 (1H, t, *J* 8.0 Hz, ArC*H*), 7.42–7.47 (1H, t, *J* 7.6 Hz, ArC*H*), 7.49–7.53 (1H, m, ArC*H*), 7.58–7.61 (1H, d, *J* 7.6 Hz, ArC*H*), 7.95–7.97 (1H, d, *J* 8.0 Hz, ArC*H*), 8.33 (1H, d, *J* 5.6 Hz, ArC*H*), 8.50 (1H, s, ArC*H*); δ$_C$ ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 21.5 (*C*H$_3$), 61.5 (*C*H), 78.7 (*C*C), 88.4 (*C*C), 94.9 (*C*C), 96.2 (*C*C), 119.9 (*C*Ar), 123.4 (*C*Ar), 124.0 (*C*Ar), 124.1 (Ar*C*H), 128.1 (Ar*C*H), 128.5 (2xAr*C*H), 128.7 (Ar*C*H), 130.9 (Ar*C*H), 131.5 (*C*Ar), 131.8 (2xAr*C*H), 132.2 (Ar*C*H), 134.2 (Ar*C*H), 145.5 (*C*Ar), 149.6 (Ar*C*H), 153.7 (Ar*C*H), 165.19 (*C*O); +ve; HRMS; ESI; m/z, calculated for C$_{24}$H$_{17}$^{35}ClNO$_2$; [M+H]$^+$; requires 386.0942, found 386.0944.

$C_{48}H_{38}CoO_2P$
Mol. Wt.: 736.7211
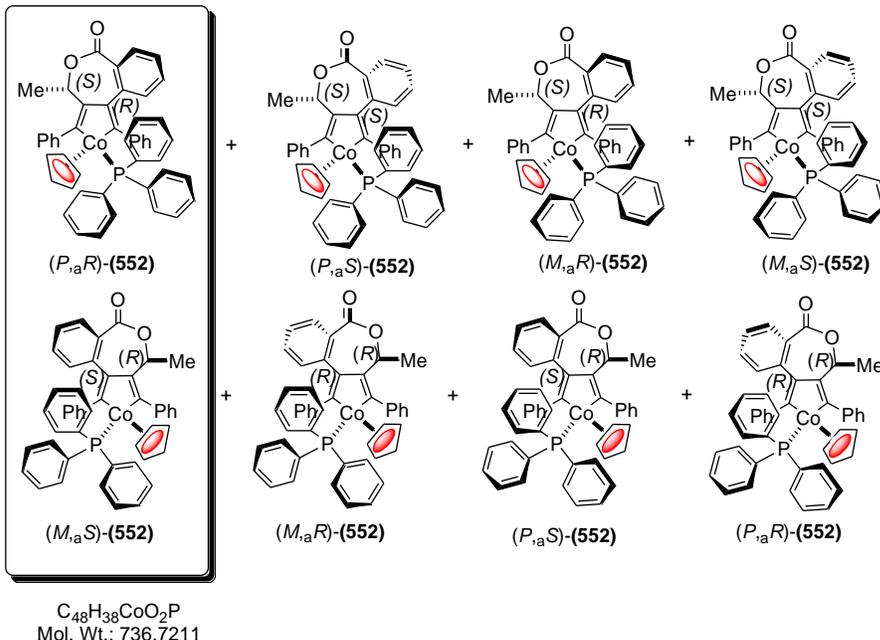
$(S_C,R_{Co},P)^*$–**(552)** or $(R_C,S_{Co},M)^*$–**(552)**, (*)= relative stereochemistry because central carbon chirality is racemic.

Using the general procedure in **section 5.7a(i)**, *rac*–4–phenylbut–3–yn–2–yl 2–(phenylethynyl)benzoate **(345)** (0.57 g, 1.61 mmol) gave $(S_C,R_{Co},P)^*$–**(552)** (0.53 g, 45%) as a red solid after silica gel column chromatography using 3:7 EtOAc/hexane. [Note: *d.r.*= 11(a):1(b):1(b):1(b), (a)= $(P,_aR)$, (b)= $(P,_aS)$, $(M,_aR)$, $(M,_aS)$] where *P*= conformational propeller chirality, $_aR$= axial chirality. $(S_C,R_{Co},P)^*$–**(552)** is a known compound and the NMR data are in agreement with the literature [202] and are given below for information.

Using the general procedure in **section 5.7b**, *rac*–4–phenylbut–3–yn–2–yl 2–(phenylethynyl)benzoate **(345)** (0.30 g, 0.86 mmol) gave $(S_C,R_{Co},P)^*$–**(552)** (0.47 g, 75%).

$(S_C,R_{Co},P)^*$–**(552)**: δ_H ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 0.47 (3H, d, *J* 6.9 Hz, (b)–C*H*$_3$), 0.62 (3H, d, *J* 7.4 Hz, (b)–C*H*$_3$), 1.12 (3H, d, *J* 7.2 Hz, (a)–C*H*$_3$), 4.51 (5H, s, (b)–C$_5$*H*$_5$), 4.63 (5H, s, (b)–C$_5$*H*$_5$), 4.80 (5H, s, (a)–C$_5$*H*$_5$), 4.83 (5H, s, (b)–C$_5$*H*$_5$), 5.00 (1H, q, *J* 7.2 Hz, (a)–C*H*), 6.01 (1H, d, *J* 7.7 Hz, ArC*H*), 6.26 (2H, t, *J* 8.4 Hz, ArC*H*), 6.55 (1H, t, *J* 6.7 Hz, ArC*H*), 6.85–7.02 (10H, m, ArC*H*), 7.11–7.62 (15H, m, ArC*H*); δ_C ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 20.3 ((a)–*C*H$_3$), 24.6, 58.6, 75.3, 81.3, 89.6 ((a)–*C*$_5$H$_5$), 90.0, 90.2, 90.5, 124.3 (Ar), 125.0 (Ar), 126.2 (Ar), 127.5 (Ar), 127.6 (Ar), 127.8 (Ar), 128.3 (Ar), 128.5 (Ar), 128.7 (Ar), 129.4 (Ar), 130.0 (Ar), 130.4 (Ar), 130.8 (Ar), 131.1 (Ar), 131.7 (Ar), 132.1 (Ar), 132.3 (Ar), 132.5 (Ar), 133.1 (Ar), 133.4 (Ar), 133.9 (Ar), 138.0 (Ar), 151.2, 152.6, 154.7, 172.4; δ_P ^{31}P NMR (δ, 109 MHz, CDCl$_3$); 49.3 (a)–(*P*Ph$_3$).

$C_{48}H_{38}CoO_2P$
Mol. Wt.: 736.7211
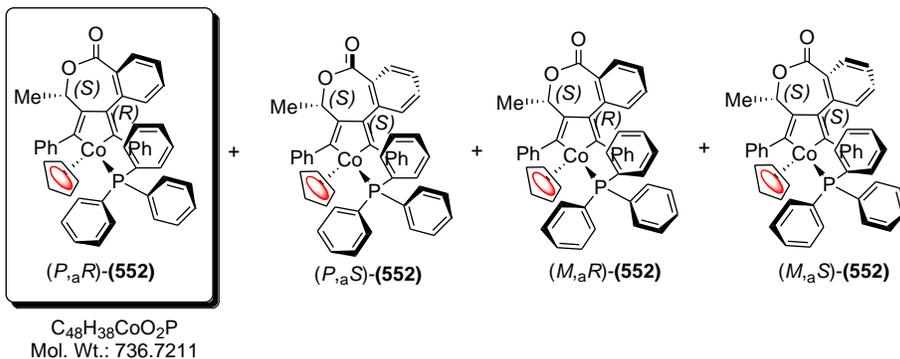
Using the general procedure in **section 5.7a(i)**, (*S*)–(–)–4–phenylbut–3–yn–2–yl 2–(phenylethynyl)benzoate **(345)** (0.50 g, 1.43 mmol) gave (S_C,R_{Co},P)–**(552)** (0.78 g, 74%) as a red solid after silica gel column chromatography using 3:7 EtOAc/hexane. [Note: *d.r.*= 11(a):1(b):1(b):1(b)].

Using the general procedure in **section 5.7b**, (*S*)–(–)–4–phenylbut–3–yn–2–yl 2–(phenylethynyl)benzoate **(345)** (0.10 g, 0.29 mmol) gave (S_C,R_{Co},P)–**(552)** (0.19 g, 81%).

(S_C,R_{Co},P)–(–)–**(552)**: m.p. 180–182°C; $[\alpha]_D$ = –746.0 (*c* 0.002, 22.8°C, CHCl$_3$); Anal. Calc. for $C_{48}H_{38}O_2CoP$, Calc.; C, 78.25; H, 5.20; Found; C, 78.18; H, 5.29; δ_H ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 0.47 (3H, d, *J* 6.9 Hz, (b)–C*H*$_3$), 0.62 (3H, d, *J* 7.4 Hz, (b)–C*H*$_3$), 1.12 (3H, d, *J* 7.2 Hz, (a)–C*H*$_3$), 4.51 (5H, s, (b)–C$_5$*H*$_5$), 4.63 (5H, s, (b)–C$_5$*H*$_5$), 4.80 (5H, s, (a)–C$_5$*H*$_5$), 4.83 (5H, s, (b)–C$_5$*H*$_5$), 5.00 (1H, q, *J* 7.2 Hz, (a)–C*H*), 6.01 (1H, d, *J* 7.7 Hz, ArC*H*), 6.26 (2H, t, *J* 8.4 Hz, ArC*H*), 6.55 (1H, t, *J* 6.7 Hz, ArC*H*), 6.85–7.02 (10H, m, ArC*H*), 7.11–7.62 (15H, m, ArC*H*); δ_C ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 20.4 ((a)–*C*H$_3$), 75.4 (*C*H), 88.7 ((a)–*C*$_5$H$_5$), 90.1, 90.3, 90.7, 124.4 (Ar), 124.5 (Ar), 125.1 (Ar), 126.3 (Ar), 126.8 (Ar), 127.6 (Ar), 127.7 (Ar), 128.0 (Ar), 128.1 (Ar), 128.5 (Ar), 128.6 (Ar), 128.7 (Ar), 129.5 (Ar), 130.2 (Ar), 130.6 (Ar), 130.9 (Ar), 131.2 (Ar), 131.9 (Ar), 132.5 (Ar), 132.6 (Ar), 133.3 (Ar), 133.6 (Ar), 133.9 (Ar), 134.0 (Ar), 134.1 (Ar), 137.3 (Ar), 137.7 (Ar), 138.0 (Ar), 150.1, 151.3, 152.7, 154.8, 169.9, 170.2, 172.5, 180.4, 180.7; ^{31}P NMR (δ, 122 MHz, CDCl$_3$); 48.6 (a)–(*P*Ph$_3$); +ve; HRMS; NESI; LSIMS; pFAB (NOBA); m/z, calculated for $C_{48}H_{38}O_2CoP$; [M]$^+$; requires 736.1942, found 736.1942; HPLC (CHIRALCEL OD) 96.5:3.5 hexane/isopropyl alcohol, 1 mL/min R$_t$= 30 min 30 secs (*S*–enantiomer), R$_t$= 34 min 48 sec (*R*–enantiomer).

$C_{47}H_{36}CoO_2P$
Mol. Wt.: 722.6945
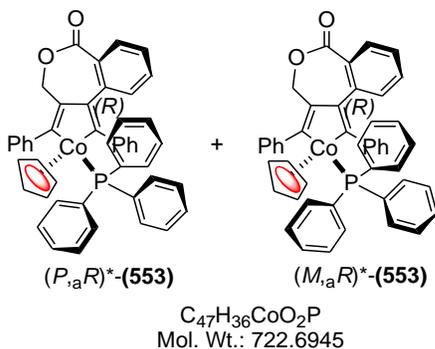
Using the general procedure in **section 5.7a(i)**, 3–phenylprop–2–ynyl 2–(phenylethynyl)benzoate **(533)** (0.30 g, 0.90 mmol) gave **(553)** (0.26 g, 40%) as a red solid after silica gel column chromatography using 3:7 EtOAc/hexane. [Note: *d.r.*= $(P,_aR)^*$ 2: $(M,_aR)^*$1].

(553): IR (thin film) v_{max} 1699 cm⁻¹; δ_H¹H NMR (δ, 270 MHz, CDCl₃); 3.95 (1H, d, *J* 11.6 Hz, $(P,_aR)^*$–C*H*), 4.25 (1H, d, *J* 11.6 Hz, $(P,_aR)^*$–C*H*), 4.48 (2H, m, $(M,_aR)^*$–C*H₂*), 4.85 (5H, s, $(P,_aR)^*$–C₅*H*₅), 4.85 (5H, s, $(M,_aR)^*$–C₅*H*₅), 6.30–7.66 (29H, m, ArC*H*); δ_C¹³C NMR (δ, 100 MHz, CDCl₃); 65.2 ($(P,_aR)^*$–*C*H₂), 65.8 ($(M,_aR)^*$–*C*H₂), 89.4 ($(M,_aR)^*$–*C*₅H₅), 89.8 ($(P,_aR)^*$–*C*₅H₅), 124.0 (Ar), 124.4 (Ar), 124.9 (Ar), 125.0 (Ar), 125.2 (Ar), 125.8 (Ar), 126.6 (Ar), 127.4 (Ar), 127.6 (Ar), 127.8 (Ar), 127.9 (Ar), 128.1 (Ar), 128.2 (Ar), 128.5 (Ar), 128.6 (Ar), 129.0 (Ar), 129.3 (Ar), 129.9 (Ar), 130.1 (Ar), 130.3 (Ar), 130.7 (Ar), 130.9 (Ar), 131.2 (Ar), 131.5 (Ar), 131.9 (Ar), 132.1 (Ar), 132.2 (Ar), 132.4 (Ar), 132.5 (Ar), 132.8 (Ar), 133.2 (Ar), 133.7 (Ar), 133.8 (Ar), 136.7 (Ar), 137.1 (Ar), 138.0 (Ar), 138.2 (Ar), 150.9, 151.0, 151.1, 151.5, 152.5, 152.9, 153.7, 173.7, 178.8, 179.1; δ_P ³¹P NMR (δ, 162 MHz, CDCl₃); 49.0 ($(M,_aR)^*$–*P*Ph₃), 54.3 ($(P,_aR)^*$–*P*Ph₃); +ve; HRMS; NESI; LSIMS; pFAB (NOBA); m/z, calculated for $C_{47}H_{36}O_2CoP$; [M]⁺; requires 722.1779, found 722.1783.

$C_{49}H_{37}CoF_3O_2P$
Mol. Wt.: 804.7191
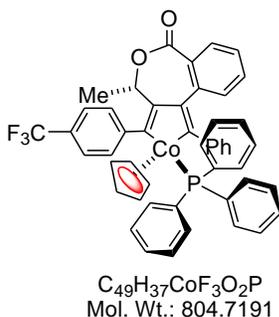
$(S_C,R_{Co},P)^*$–**(555)**.

Using the general procedure in **section 5.7a(i)**, *rac*–4–(4–(trifluoromethyl)phenyl)but–3–yn–2–yl 2–(phenylethynyl)benzoate **(535)** (0.14 g, 0.34 mmol) gave complex $(S_C,R_{Co},P)^*$–**(555)** (0.21 g, 76%) as a bright red solid after silica gel column chromatography using 3:7 EtOAc/hexane as the elutant solvent mixture. [Note: *d.r.*= 17(a):1(b):1(b):1(b)].

$(S_C,R_{Co},P)^*$–**(555)**: IR (thin film) v_{max}; 1693 cm⁻¹; δ_H ¹H NMR (δ, 270 MHz, CDCl₃); 0.51 (3H, d, *J* 6.9 Hz, (b)–C*H₃*), 0.70 (3H, d, *J* 7.4 Hz, (b)–C*H₃*), 0.91 (3H, d, *J* 8.2 Hz, (b)–C*H₃*), 1.13 (3H, d, *J* 7.2 Hz, (a)–C*H₃*), 4.52 (5H, s, (b)–C₅*H*₅), 4.64 (5H, s, (b)–C₅*H*₅), 4.82 (5H, s, (a)–C₅*H*₅), 4.84 (5H, s, (b)–C₅*H*₅), 4.93 (1H, q, *J* 7.2 Hz, (a)–C*H*), 6.12 (1H, d, *J* 8.2 Hz,

ArC*H*), 6.25 (2H, t, *J* 9.9 Hz, ArC*H*), 6.79–7.63 (25H, m, ArC*H*); δ_C ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 20.1, 21.0, 22.7, 29.4, 29.7, 31.9, 75.0, 89.6 ((a)–C_5H_5), 89.9 ((b)–C_5H_5), 90.1 ((b)–C_5H_5), 90.4 ((b)–C_5H_5), 123.3 (Ar), 124.3 (Ar), 124.5 (Ar), 125.1 (Ar), 125.4 (Ar), 125.9 (Ar), 126.0 (Ar), 126.2 (Ar), 127.7 (Ar), 127.9 (Ar), 128.0 (Ar), 128.1 (Ar), 128.2 (Ar), 128.3 (Ar), 128.4 (Ar), 128.6 (Ar), 128.7 (Ar), 129.5 (Ar), 129.8 (Ar), 130.2 (Ar), 130.5 (Ar), 130.8 (Ar), 131.0 (Ar), 131.1 (Ar), 131.5 (Ar), 132.2 (Ar), 132.3 (Ar), 132.5 (Ar), 133.0 (Ar), 133.5 (Ar), 133.6 (Ar), 133.7 (Ar), 133.8 (Ar), 137.0 (Ar), 137.4 (Ar), 137.7 (Ar), 150.0, 152.4, 154.9, 166.5, 166.8; δ_F ^{19}F NMR (δ, 376 MHz, CDCl$_3$); –63.0 (b), –63.9 (b), –63.5 (a); δ_P ^{31}P NMR (δ, 109 MHz, CDCl$_3$); 48.6 (a)–(*P*Ph$_3$), 49.4 (b)–(*P*Ph$_3$), 49.5 (b)–(*P*Ph$_3$); +ve; HRMS; LSIMS; FAB (NOBA); m/z, calculated for C$_{49}$H$_{37}$CoF$_3$O$_2$P; [M]$^+$; requires 804.1810, found 804.1809.

C$_{49}$H$_{37}$CoF$_3$O$_2$P
Mol. Wt.: 804.7191
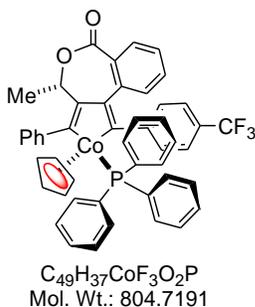
(S_C,R_{Co},P)*–(**556**).

Using the general procedure in **section 5.7a(i)**, *rac*–4–phenylbut–3–yn–2–yl 2–((4–(trifluoromethyl)phenyl) ethynyl) benzoate (**536**) (0.08 g, 0.18 mmol) gave complex (S_C,R_{Co},P)*–(**556**) (0.11 g, 75%) as a bright red crystalline solid after silica gel column chromatography using 3:7 EtOAc/hexane as the elutant solvent mixture. [Note: *d.r.*= 11(a):1(b):1(b):1(b)].

Using the general procedure in **section 5.7b**, *rac*–4–phenylbut–3–yn–2–yl 2–((4–(trifluoromethyl)phenyl)ethynyl) benzoate (**536**) (0.09 g, 0.21 mmol) gave complex (S_C,R_{Co},P)*–(**556**) (0.14 g, 81%).

(S_C,R_{Co},P)*–(**556**): m.p. 178–180°C; IR (thin film) v$_{max}$; 1733 cm^{-1}; δ_H ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 0.42 (3H, d, *J* 6.7 Hz, (b)–C*H*$_3$), 0.58 (3H, d, *J* 7.4 Hz, (b)–C*H*$_3$), 1.12 (3H, d, *J* 7.2 Hz, (a)–C*H*$_3$), 1.53 (3H, d, *J* 6.4 Hz, (b)–C*H*$_3$), 4.50 (5H, s, (b)–C_5H_5), 4.62 (5H, s, (b)–C_5H_5), 4.80 (5H, s, (a)–C_5H_5), 4.83 (5H, s, (b)–C_5H_5), 4.99 (1H, q, *J* 7.2 Hz, (a)–C*H*), 5.95 (1H, d, *J* 8.0 Hz, ArC*H*), 6.25 (2H, t, *J* 9.6 Hz, ArC*H*), 6.60 (1H, *J* 8.0 Hz, ArC*H*), 6.80–7.69 (24H, m, ArC*H*); δ_C ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 20.2 (CH$_3$), 75.3 (CH), 82.1, 89.7 ((a)–C_5H_5), 90.1 ((b)–C_5H_5), 90.5 ((b)–C_5H_5), 124.4 (Ar), 124.6 (Ar), 125.5 (Ar), 126.1 (Ar), 127.7 (Ar), 127.9 (Ar), 128.0 (Ar), 128.5 (Ar), 128.7 (Ar), 129.7 (Ar), 130.2 (Ar), 130.5 (Ar), 130.8 (Ar), 131.0 (Ar), 131.2 (Ar), 132.1 (Ar), 132.3 (Ar), 133.0 (Ar), 133.5 (Ar), 133.7 (Ar), 133.8 (Ar), 134.0 (Ar), 135.7 (Ar), 136.4 (Ar), 137.3 (Ar), 151.0, 151.2, 154.6, 156.5, 171.7, 172.0, 172.1, 176.2, 176.6; δ_F ^{19}F NMR (δ, 376 MHz, CDCl$_3$) –63.2 (b), –63.1 (b), –63.3 (a), ; δ_P ^{31}P NMR (δ, 109 MHz, CDCl$_3$); 48.5 (a)–(*P*Ph$_3$), 51.9 (b)–(*P*Ph$_3$), 55.0 (b)–(*P*Ph$_3$); +ve; HRMS; NESI, LSIMS; pFAB (NOBA), m/z, calculated for C$_{49}$H$_{37}$CoF$_3$O$_2$P; [M]$^+$; requires 804.1810, found 804.1805.
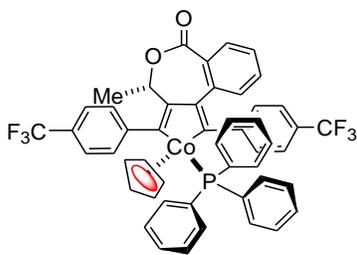
C$_{50}$H$_{36}$CoF$_6$O$_2$P
Mol. Wt.: 872.7170

(S_C,R_{Co},P)*–**(557)**.

Using the general procedure in **section 5.7a(i)**, *rac*–4–(4–(trifluoromethyl)phenyl)but–3–yn–2–yl 2–((4–(trifluoromethyl)phenyl)ethynyl) benzoate **(537)** (0.60 g, 1.23 mmol) gave complex (S_C,R_{Co},P)*–**(557)** (0.70 g, 65%) as a bright red crystalline after silica gel column chromatography using 3:7 EtOAc/hexane as the elutant solvent mixture. [Note: *d.r.*= 15(a):1(b):1(b)].

(S_C,R_{Co},P)*–**(557)**: IR (thin film) ν$_{max}$; 1693 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 0.48 (3H, d, *J* 6.7 Hz, (b)–C*H*$_3$), 0.68 (3H, d, *J* 7.4 Hz, (b)–C*H*$_3$), 1.14 (3H, d, *J* 7.2 Hz, (a)–C*H*$_3$), 4.52 (5H, s, (b)–C$_5$*H*$_5$)), 4.65 (5H, s, (b)–C$_5$*H*$_5$), 4.84 (5H, s, (a)–C$_5$*H*$_5$), 4.95 (1H, q, *J* 7.2 Hz, (a)–C*H*), 6.09 (1H, d, *J* 7.9, ArC*H*), 6.25 (2H, t, *J* 10.1, ArC*H*), 6.60–8.00 (24H, m, ArC*H*); δ$_C$ ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 20.0 ((a)–*C*H$_3$), 60.4 (*C*H), 74.9, 75.0, 89.6 ((a)–*C*$_5$H$_5$), 89.9 ((b)–*C*$_5$H$_5$), 90.0 ((c)–*C*$_5$H$_5$), 90.3, 123.2 (Ar), 124.4 (Ar), 124.5 (Ar), 125.6 (Ar), 125.9 (Ar), 126.2 (Ar), 126.6 (Ar), 127.6 (Ar), 128.0 (Ar), 128.1 (Ar), 128.4 (Ar), 128.5 (Ar), 128.7 (Ar), 128.8 (Ar), 129.5 (Ar), 129.8 (Ar), 129.9 (Ar), 130.1 (Ar), 130.4 (Ar), 130.5 (Ar), 130.6 (Ar), 130.8 (Ar), 131.0 (Ar), 131.1 (Ar), 131.3 (Ar), 131.7 (Ar), 132.1 (Ar), 132.2 (Ar), 132.8 (Ar), 133.0 (Ar), 133.2 (Ar), 133.4 (Ar), 133.5 (Ar), 133.7 (Ar), 133.8 (Ar), 135.8 (Ar), 136.3 (Ar), 137.1 (Ar), 151.2, 154.7, 155.0, 156.2, 168.3, 168.5; δ$_F$ ^{19}F NMR (δ, 376 MHz, CDCl$_3$); –62.6 (b), –62.1 (a), –62.7 (b), –62.1 (a); δ$_P$^{31}P NMR (δ, 109 MHz, CDCl$_3$); 48.0 (a)–(*P*Ph$_3$); +ve; HRMS; LSIMS; pFAB (NOBA); m/z, calculated for C$_{50}$H$_{36}$CoF$_6$O$_2$P; [M]$^+$; requires 872.1683, found 872.1684.
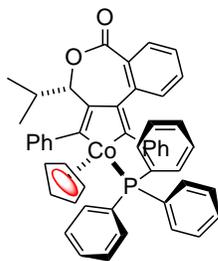
C$_{50}$H$_{42}$CoO$_2$P
Mol. Wt.: 764.7742
(S_C,R_{Co},P)*–**(558)**.

Using the general procedure in **section 5.7a(i)**, *rac*–4–methyl–1–phenylpent–1–yn–3–yl 2–(phenylethynyl)benzoate **(346)** (1.00 g, 2.63 mmol) gave **(558)** as a dark red crystalline solid (1.11 g, 55%) after silica gel column chromatography using 3:7 EtOAc/hexane. [Note: *d.r.*= 1:0].

Using the general procedure in **section 5.7b**, *rac*–4–methyl–1–phenylpent–1–yn–3–yl 2–(phenylethynyl)benzoate **(346)** (0.25 g, 0.66 mmol) gave **(558)** as a dark red crystalline solid (0.40 g, 80%).

Using the general procedure in **section 5.7c**, *rac*–4–methyl–1–phenylpent–1–yn–3–yl 2–(phenylethynyl)benzoate **(346)** (0.25 g, 0.66 mmol) gave **(558)** (0.45 g, 90%).

(S_C,R_{Co},P)*–**(558)**: m.p. 208–21°C; Anal. Calc. for $C_{50}H_{42}O_2PCo$, Calc.; C, 78.52; H, 5.54; Found; C, 78.42; H, 5.54; IR (thin film) v_{max} ;1734 cm^{-1}; δ_H ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 0.60 (3H, d, *J* 6.4 Hz, C*H*$_3$), 0.65 (3H, d, *J* 6.4 Hz, C*H*$_3$), 1.06–1.26 (1H, m, C*H*), 4.28 (1H, d, *J* 11.2 Hz, CH), 4.81 (5H, s, C$_5$*H*$_5$), 5.96 (1H, d, *J* 7.6 Hz, ArC*H*), 6.18 (2H, t, *J* 10.4 Hz, ArC*H*), 6.41 (1H, t, *J* 7.6 Hz, ArC*H*), 6.66 (2H, t, *J* 10.8 Hz, ArC*H*), 6.83–6.90 (10H, m, ArC*H*), 6.96 (1H, t, *J* 6.8 Hz, ArC*H*), 7.11 (3H, t, *J* 8.8 Hz, ArC*H*), 7.17–7.28 (7H, m, ArC*H*), 7.38 (1H, t, *J* 7.2 Hz, ArC*H*), 7.56 (1H, d, *J* 8.0 Hz, ArC*H*); δ_C ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 19.6 (*C*H$_3$), 20.5 (*C*H$_3$), 29.9 (*C*H), 85.4, 85.5, 89.7 (*C*$_5$H$_5$), 124.2 (Ar), 124.4 (Ar), 125.2 (Ar), 126.7 (Ar), 127.3 (Ar), 127.7 (Ar), 128.0 (Ar), 128.2 (Ar), 128.3 (Ar), 128.6 (Ar), 128.7 (Ar), 129.4 (Ar), 129.9 (Ar), 130.4 (Ar), 130.6 (Ar), 130.7 (Ar), 130.9 (Ar), 131.1 (Ar), 131.2 (Ar), 132.4 (Ar), 132.5 (Ar), 132.9 (Ar), 133.0 (Ar), 133.8 (Ar), 133.9 (Ar), 134.0 (Ar), 134.1 (Ar), 137.1 (Ar), 137.5 (Ar), 138.3 (Ar), 138.3 (Ar), 150.0 (Ar), 150.8 (Ar), 152.7, 152.8, 152.9, 171.5, 171.8, 172.7, 180.5, 180.8; δ_P ^{31}P NMR (δ, 162 MHz, CDCl$_3$); 49.6 (*P*Ph$_3$); +ve; HRMS; LSIMS; pFAB (NOBA); m/z, calculated for $C_{50}H_{42}O_2PCo$; [M]$^+$; requires 764.2249, found 764.2238.

$C_{51}H_{44}CoO_2P$
Mol. Wt.: 778.8008
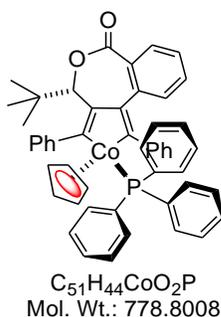
(S_C,R_{Co},P)*–**(559)**.

Using the general procedure in **section 5.7a(i)**, *rac*–4,4–dimethyl–1–phenylpent–1–yn–3–yl 2–(phenylethynyl)benzoate **(538)** (0.50 g, 1.26 mmol) gave (S_C,R_{Co},P)*–**(559)** (0.42 g, 43%) as a dark red crystalline solid after silica gel column chromatography using 3:7 EtOAc /hexane. [Note: *d.r.*= 18(a):5(b):2(c)].

(S_C,R_{Co},P)*–**(559)**: m.p.210–212°C; δ_H ^{1}H NMR (δ, 400 MHz, CDCl$_3$); Anal. Calc. for $C_{51}H_{44}O_2PCo$·1.6(H$_2$O), Calc.; C, 73.61; H, 5.57; Found; C, 73.47; H, 5.74; IR (thin film) v_{max}; 1780 cm^{-1}; δ_H ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.45 (9H, s, (C*H*$_3$)$_3$C), 4.68 (5H, s, (c)–C$_5$*H*$_5$), 4.81 (5H, s, (a)–C$_5$*H*$_5$), 4.84 (5H, s, (b)–C$_5$*H*$_5$), 5.85 (1H, d, *J* 7.6 Hz, ArC*H*), 6.20 (3H, m, (a)–C*H*, ArC*H*), 6.39 (1H, t, *J* 7.6 Hz, ArC*H*), 6.48 (2H, t, *J* 10.8 Hz, ArC*H*), 6.80–6.99 (10H, m, ArC*H*), 7.10–7.65 (13H, m, ArC*H*); δ_C ^{13}C NMR (δ, 100 MHz, CD$_2$Cl$_2$); 28.8 ((CH$_3$)$_3$C), 30.0, 32.3, 37.6, 65.8, 68.3, 83.2 ((c)–C$_5$H$_5$)), 87.1, 87.2, 87.5 ((b)–C$_5$H$_5$)), 90.1 ((a)–C$_5$H$_5$)), 91.2, 92.8, 124.3 (Ar), 125.0 (Ar), 126.9 (Ar), 127.3 (Ar), 127.5 (Ar), 127.7 (Ar), 128.1 (Ar), 128.2 (Ar), 128.3 (Ar), 128.6 (Ar), 129.0 (Ar), 129.1 (Ar), 129.2 (Ar), 129.6 (Ar), 130.0 (Ar), 130.3 (Ar), 130.7

(Ar), 130.9 (Ar), 131.1 (Ar), 131.3 (Ar), 131.5 (Ar), 131.7 (Ar), 131.9 (Ar), 132.3 (Ar), 132.6 (Ar), 132.7 (Ar), 132.8 (Ar), 133.2 (Ar), 133.4 (Ar), 133.7 (Ar), 134.1 (Ar), 134.4 (Ar), 134.5 (Ar), 135.1 (Ar), 150.9 (Ar), 151.1 (Ar), 151.3 (Ar), 153.3 (Ar), 170.4, 172.5, 175.5, 175.7, 180.5, 180.8; δ_P ^{31}P NMR (δ, 162 MHz, CDCl$_3$); 49.6 (PPh$_3$); +ve; HRMS; LSIMS; pFAB (NOBA); m/z, calculated for C$_{51}$H$_{44}$CoO$_2$P; [M]$^+$; requires 778.2404, found 778.2405.

C$_{46}$H$_{42}$CoO$_2$P
Mol. Wt.: 716.7314
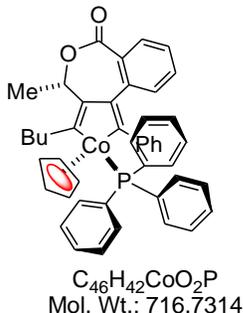
(S_C,R_{Co},P)*–(560).

Using the general procedure in **section 5.7a(i)**, *rac*–oct–3–yn–2–yl 2–(phenylethynyl)benzoate **(539)** (0.09 g, 0.28 mmol) gave complex **(560)** (0.12 g, 60%) as a bright red crystalline solid after silica gel column chromatography using 3:7 EtOAc/hexane.

(S_C,R_{Co},P)*–(560): IR (thin film) v$_{max}$; 2924, 1734 cm^{-1}; δ_H ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 0.76 (3H, t, *J* 6.9 Hz, C*H*$_3$), 0.84–0.91 (4H, m, 2xC*H*$_2$), 1.22–1.27 (5H, m, C*H*$_2$, C*H*$_3$), 4.89 (5H, s, C$_5$*H*$_5$), 5.51 (1H, q, *J* 7.2 Hz, C*H*), 6.89–7.66 (24H, m, ArC*H*); δ_C ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 12.7, 13.1, 19.1, 21.6, 22.4, 28.3, 28.6, 29.0, 30.9, 33.0, 40.2, 72.0, 87.5 (*C$_5$*H$_5$), 122.9 (Ar), 123.6 (Ar), 125.7 (Ar), 126.4 (Ar), 126.9 (Ar), 127.6 (Ar), 128.1 (Ar), 128.4 (Ar), 128.9 (Ar), 129.3 (Ar), 129.6 (Ar), 129.7 (Ar), 131.0 (Ar), 131.2 (Ar), 132.0 (Ar), 132.7 (Ar), 136.8 (Ar), 148.4 (Ar), 148.5 (Ar), 152.2 (Ar), 152.4 (Ar), 173.2, 173.5, 177.8, 178.1; δ_P ^{31}P NMR (δ, 162 MHz, CDCl$_3$); 52.3 (PPh$_3$); +ve; HRMS; LSIMS; pFAB (NOBA); m/z, calculated for C$_{46}$H$_{42}$CoO$_2$P; [M]$^+$; requires 716.2249, found 716.2249.

C$_{47}$H$_{37}$CoNO$_2$P
Mol. Wt.: 737.7091
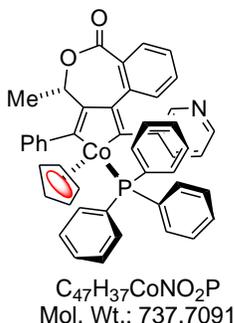
(S_C,R_{Co},P)*–(563).

Using the general procedure in **section 5.7b**, 4–phenylbut–3–yn–2–yl 2–(pyridin–3–yl ethynyl)benzoate **(542)** (0.30 g, 0.85 mmol) gave (S_C,R_{Co},P)*–(563) (0.56 g, 90%) as a bright red crystalline solid after silica gel column chromatography using 3:7 EtOAc/hexane as the elutant. [*d.r.*=10(a):2 (b): 1 (c):1(c)]

(S_C,R_{Co},P)*–(563): m.p. 206–208°C; Anal. Calc. for $C_{47}H_{37}NCoO_2P\cdot0.11(H_2O)$; Calc.; C, 76.32; H, 5.07; N, 1.89; Found; C, 76.32; H, 5.09; N, 1.87; IR (thin film) v_{max}; 3057, 2927, 1700 cm^{-1}; δ_H ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.04 (3H, d, J 7.3 Hz, CH_3), 4.47 (5H, s, (b)–C$_5H_5$), 4.59 (5H, s, (b)–C$_5H_5$), 4.76 (5H, s, (b)–C$_5H_5$), 4.80–04.90 (5H, brs, (a)–C$_5H_5$), 4.92 (1H, q, J 7.3 Hz, (a)–CH), 5.90 (1H, d, J 9.0 Hz, ArCH), 6.26 (2H, brs, ArCH), 6.55 (1H, t, J 9.0 Hz, ArCH), 6.76–7.58 (24H, m, ArCH); δ_C ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 20.3 (CH_3), 22.9, 29.9, 32.1, 75.4, 82.1, 89.9 ((a)–C$_5H_5$), 124.7 (Ar), 125.7 (Ar), 127.7 (Ar), 127.8 (Ar), 128.1 (Ar), 128.4 (Ar), 128.5 (Ar), 128.6 (Ar), 128.8 (Ar), 129.8 (Ar), 130.3 (Ar), 130.8 (Ar), 131.1 (Ar), 131.3 (Ar), 131.6 (Ar), 132.3 (Ar), 133.3 (Ar), 133.6 (Ar), 137.0, 151.0, 154.9, 172.0 (CO); δ_P ^{31}P NMR (δ, 162 MHz, CDCl$_3$); 49.4 (a)–(PPh$_3$), 51.3 (b)–(PPh$_3$); +ve; HRMS; LSIMS; pFAB (NOBA); m/z, calculated for $C_{47}H_{37}CoNO_2P$; [M]$^+$; requires 738.1957, found 738.1967,.

C$_{49}$H$_{40}$CoO$_3$P
Mol. Wt.: 766.7471
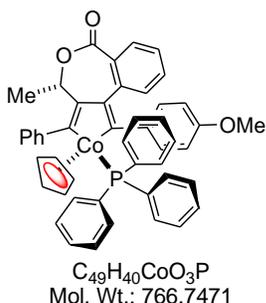
(S_C,R_{Co},P)*–(564).
Using the general procedure in **section 5.7b**, 4–phenylbut–3–yn–2–yl 2–(4–methoxyphenyl)ethynyl)benzoate (543) (0.30 g, 0.79 mmol) (S_C,R_{Co},P)*–(564) (0.45 g, 74%) as a bright red crystalline solid after silica gel column chromatography using 3:7 EtOAc/hexane. [Note: *d.r.*= 13(a):1(b): 1(b):1(b)

(S_C,R_{Co},P)*–(564): m.p. 150–152°C; IR (thin film) v_{max}; 1693 cm^{-1}; δ_H ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 0.36 (3H, d, J 6.0 Hz, (b)–CH_3), 0.50 (3H, d, J 6.8 Hz, (b)–CH_3), 1.02 (3H, d, J 6.8 Hz, (a)–CH_3), 3.60 (3H, s, (a)–OCH_3), 4.42 (5H, s, (b)–C$_5H_5$), 4.54 (5H, s, (b)–C$_5H_5$), 4.71 (5H, s, (a)–C$_5H_5$), 4.91 (1H, m, CH), 5.91–7.71 (27H, m, ArCH); δ_C ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 19.2 (CH_3), 28.6, 54.1, 59.3, 74.1, 80.1, 88.5 ((a)–C$_5H_5$), 88.7 ((b)–C$_5H_5$), 89.1 ((b)–C$_5H_5$), 89.5 ((b)–C$_5H_5$), 111.9, 112.9, 123.1 (Ar), 123.7 (Ar), 125.1 (Ar), 126.3 (Ar), 126.4 (Ar), 126.7 (Ar), 126.7 (Ar), 126.8 (Ar), 127.2 (Ar), 127.3 (Ar), 127.4 (Ar), 127.5 (Ar), 128.2 (Ar), 128.9 (Ar), 129.0 (Ar), 129.2 (Ar), 129.4 (Ar), 129.6 (Ar), 129.8 (Ar), 129.9 (Ar), 130.6 (Ar), 130.8 (Ar), 130.9 (Ar), 131.0 (Ar), 131.1 (Ar), 131.3 (Ar), 131.4 (Ar), 132.0 (Ar), 132.2 (Ar), 132.4 (Ar), 132.6 (Ar), 132.7 (Ar), 132.8 (Ar), 136.0 (Ar), 136.4 (Ar), 136.9 (Ar), 137.0 (Ar), 138.6 (Ar), 144.2 (Ar), 145.6 (Ar), 145.8 (Ar), 148.6 (Ar), 150.2, 153.3, 155.7, 168.7, 169.0, 170.1, 171.4, 179.5, 179.8; δ_P ^{31}P NMR (δ, 162 MHz, CDCl$_3$); 49.5 (a)–(PPh$_3$), 50.2 (b)–(PPh$_3$), 52.7 (b)–(PPh$_3$), 56.6 (b)–(PPh$_3$); +ve; HRMS; LSIMS; pFAB (NOBA); m/z, calculated for $C_{49}H_{40}CoO_3P$; [M]$^+$; requires 767.2111, found 767.2120.
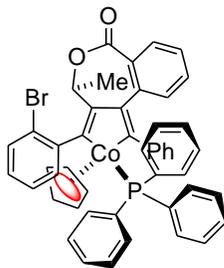
C$_{48}$H$_{37}$BrCoO$_2$P
Mol. Wt.: 815.6171

(S_C,R_{Co},P)*–**(566)**.

Using the general procedure in **section 5.7a(i)**, 4–(2–bromophenyl)but–3–yn–2–yl 2–(phenylethynyl)benzoate **(548)** (0.31 g, 0.72 mmol) gave (S_C,R_{Co},P)*–**(566)** (0.43 g, 73%) as a bright red crystalline solid after silica gel column chromatography using 3:7 EtOAc/hexane. [Note: 7(a):2(b): 2(b): 1(c)].

Using the general procedure in **section 5.7b**, 4–(2–bromophenyl)but–3–yn–2–yl 2–(phenylethynyl)benzoate **(548)** (0.50 g, 1.17 mmol) gave (S_C,R_{Co},P)*–**(566)** (0.82 g, 86%) as a bright red crystalline solid after silica gel column chromatography using 3:7 EtOAc/hexane.

(S_C,R_{Co},P)*–**(566)**: m.p. 148–150°C; Anal. Calc. for C$_{48}$H$_{37}$BrCoO$_2$P·0.2(NaCl); Calc.; C, 70.68; H, 4.57; Found; C, 70.74; H,4.49; IR (thin film) v$_{max}$; 1734, 1463, 1377 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 0.23 (3H, d, J 7.2 Hz, (d)–CH_3), 0.36 (3H, d, J 6.8 Hz, (b)–CH_3), 1.04 (3H, d, J 6.8 Hz, (b)–CH_3), 1.29 (3H, d, J 7.2 Hz, (a)–CH_3), 4.64 (5H, s, (b)–C$_5$$H_5$), 4.72 (5H, s, (c)–C$_5$$H_5$), 4.86 (1H, q, J 7.2 Hz, (a)–CH), 4.95 (5H, s, (b)–C$_5$$H_5$), 4.97 (5H, s, (a)–C$_5$$H_5$), 5.98 (2H, t, J 8.8 Hz, ArCH), 6.20 (1H, d, J 4.0 Hz, Ar), 6.86–6.90 (4H, m, ArCH), 7.00 (1H, t, J 9.6 Hz, ArCH), 7.08–7.57 (20H, m, ArCH); δ$_C$^{13}C NMR (δ, 100 MHz, CDCl$_3$); 19.4 (CH_3), 76.0 (CH), 76.0, 88.8 ((a)–C$_5$$H_5$), 89.1 ((b)–C$_5$$H_5$), 90.0 ((c)–C$_5$$H_5$), 121.0 (Ar), 124.6 (Ar), 125.3 (Ar), 125.9 (Ar), 126.2 (Ar), 127.9 (Ar), 128.0 (Ar), 128.6 (Ar), 128.7 (Ar), 128.8 (Ar), 128.9 (Ar), 129.4 (Ar), 130.4 (Ar), 130.6 (Ar), 130.7 (Ar), 130.8 (Ar), 131.1 (Ar), 131.3 (Ar), 131.4 (Ar), 132.2 (Ar), 132.3 (Ar), 132.5 (Ar), 132.9 (Ar), 133.1 (Ar), 133.3 (Ar), 133.5 (Ar), 134.1 (Ar), 134.2 (Ar), 134.5 (Ar), 134.6 (Ar), 138.3, 138.7, 150.2, 150.5, 152.4, 155.5, 172.4 (CO); δ$_P$ ^{31}P NMR (δ, 162 MHz, CDCl$_3$); 47.1 (PPh_3); +ve; HRMS; LSIMS; pFAB (NOBA); m/z, calculated for C$_{48}$H$_{37}$^{79}BrCoO$_2$P; [M]$^+$; requires 814.1041, found 814.1040.
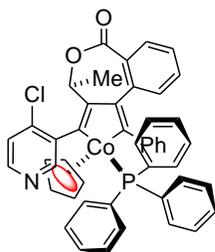
C$_{47}$H$_{36}$ClCoNO$_2$P
Mol. Wt.: 772.1542

(S_C,R_{Co},P)*–**(567)**.

Using the general procedure in **section 5.7a(i)**, 4–(4–chloropyridin–3–yl)but–3–yn–2–yl 2–(phenylethynyl)benzoate **(549)** (0.67 g, 1.65 mmol) gave (S_C,R_{Co},P)*–**(567)** (0.69 g, 54%) as a bright red crystalline solid after silica gel column chromatography using 3:7 EtOAc/hexane. [Note: *d.r.*= 16(a):2(b): 2(b):1.5(c)].

Using the general procedure in **section 5.7b**, 4–(4–chloropyridin–3–yl)but–3–yn–2–yl 2–(phenylethynyl)benzoate **(549)** (0.09 g, 0.22 mmol) gave (S_C,R_{Co},P)*–**(567)** (0.14 g, 80%) as a bright red crystalline solid after silica gel column chromatography using 3:7 EtOAc/hexane.

(S_C,R_{Co},P)*–**(567)**: m.p. 198–200°C; Anal. Calc. for $C_{47}H_{36}O_2NClCoP \cdot 1.3(H_2O)$; Calc.; C, 73.83; H, 5.09; N, 1.83; Found C, 73.21, H, 4.79, N, 1.84; IR (thin film) v_{max}: 1695, 1435, 1276 cm^{-1}; δ_H ^{1}H NMR (δ, 400 MHz, CD$_2$Cl$_2$); 0.27 (3H, brs, (c)–CH_3), 0.36 (3H, d, *J* 6.4 Hz, (b)–CH_3), 0.97 (3H, d, *J* 6.0 Hz, (b)–CH_3), 1.20 (3H, d, *J* 7.2 Hz, (a)–CH_3), 4.67 (5H, s, (b)–C$_5H_5$), 4.72 (5H, s, (c)–C$_5H_5$), 4.79 (1H, q, *J* 7.2 Hz, (a)–CH), 4.96 (5H, s, (a)–C$_5H_5$), 6.04 (2H, t, *J* 9.2 Hz, ArCH), 6.20–8.17 (25H, m, ArCH); δ_C ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 19.3, 29.9, 75.7, 88.1 ((a)–C$_5H_5$), 89.1 ((b)–C$_5H_5$), 89.8 ((b)–C$_5H_5$), 89.9 ((c)–C$_5H_5$), 124.8 (Ar), 125.4 (Ar), 125.8 (Ar), 127.9 (Ar), 128.0 (Ar), 128.1 (Ar), 128.7 (Ar), 128.8 (Ar), 128.9 (Ar), 129.0 (Ar), 129.5 (Ar), 130.2 (Ar), 130.4 (Ar), 130.7 (Ar), 130.8 (Ar), 131.1 (Ar), 131.3 (Ar), 131.4 (Ar), 132.2 (Ar), 132.3 (Ar), 137.5 (Ar), 138.0 (Ar), 138.3 (Ar), 139.5 (Ar), 146.1 (Ar), 150.3 (Ar), 152.1, 157.8, 172.0 (CO); δ_P ^{31}P NMR (δ, 162 MHz, CDCl$_3$); 47.3 (a)–(PPh$_3$), 51.9 (c)–(PPh$_3$), 54.2 (b)–(PPh$_3$); +ve; HRMS; NESI; pFAB; m/z, calculated for $C_{47}H_{37}ClCoNO_2P$; [M+H]$^+$; requires 772.1577, found 772.1572.

C$_{50}$H$_{40}$CoO$_4$P
Mol. Wt.: 794.7572
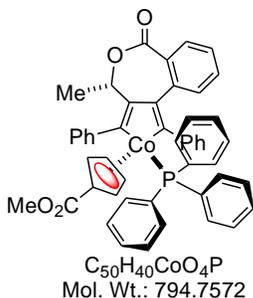
(S_C,R_{Co},P)*–**(568)**.

Using the general procedure in **section 5.7a(ii)**, *rac*–4–phenylbut–3–yn–2–yl 2–(phenylethynyl)benzoate **(345)** (0.18 g, 0.52 mmol) gave (S_C,R_{Co},P)*–**(568)** as a red solid (0.26 g, 63%) after silica gel column chromatography using 3:7 EtOAc/hexane. [Note: *d.r.*= 13(a):1(b):1(b):1(b)].

(S_C,R_{Co},P)*–**(568)**: m.p. 178–180°C; IR (thin film) v_{max}; 1694 cm^{-1}; δ_H ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 0.39 (3H, d, *J* 6.9 Hz, (b)–CH_3), 0.51 (3H, d, *J* 7.2 Hz, (b)–CH_3), 1.05 (3H, d, *J* 7.2 Hz, (a)–CH_3), 3.53 (3H, s, (b)–OCH_3), 3.57 (3H, s, (a)–OCH_3), 3.60 (3H, s, (b)–OCH_3), 3.66 (3H, s, (b)–OCH_3), 4.29 (1H, brs, CH), 4.52 (1H, brs, CH), 4.96 (1H, q, *J* 7.2 Hz, (a)–CH), 5.62 (1H, brs, CH), 6.09 (1H, brs, CH), 6.30 (2H, t, *J* 9.2 Hz, ArCH), 6.63–7.64 (27H, m, ArCH); δ_C ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 20.0 ((a)–CH_3), 29.8, 52.1, 75.3, 75.4, 77.4, 85.6, 85.6, 89.6, 91.1, 95.1, 98.6, 124.7 (Ar), 125.0 (Ar), 125.5 (Ar), 127.5 (Ar), 127.7 (Ar), 127.9 (Ar), 128.1 (Ar), 128.2 (Ar), 128.5 (Ar), 128.7 (Ar), 129.3 (Ar), 129.6 (Ar), 130.0 (Ar), 130.4 (Ar), 130.9 (Ar), 131.2 (Ar), 131.3 (Ar), 131.9 (Ar), 132.0 (Ar), 132.1 (Ar), 132.3 (Ar), 132.7 (Ar), 132.8

(Ph), 133.0 (Ar), 133.6 (Ar), 133.8 (Ar), 134.1 (Ar), 134.2 (Ar), 138.2, 138.3, 167.0, 169.6, 170.0, 172.1; δ_P ^{31}P NMR (δ, 109 MHz, CDCl$_3$); 52.6 (b)–(PPh$_3$), 50.0 (a)–(PPh$_3$), 49.2 (b)–(PPh$_3$); +ve; HRMS; LSIMS; pFAB (NOBA); m/z, calculated for C$_{50}$H$_{40}$CoO$_4$P; [M]$^+$; requires 794.1991, found 794.1995.


C$_{52}$H$_{44}$CoO$_4$P
Mol. Wt.: 822.8103
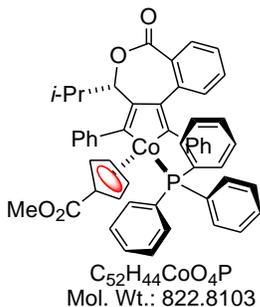
(S_C,R_{Co},P)*–(569).

Using the general procedure in **section 5.7a(ii)**, *rac*–4–methyl–1–phenylpent–1–yn–3–yl 2–(phenylethynyl)benzoate **(346)** (0.27 g, 0.71 mmol) gave (S_C,R_{Co},P)*–(569) (0.39 g, 61%) as a dark red solid after silica gel column chromatography using 3:7 EtOAc /hexane. [Note: *d.r.*= 3(a):1(b)].

(S_C,R_{Co},P)*–(569): IR (thin film) v$_{max}$; 1733 cm^{-1}; δ_H ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.16 (3H, m, (a)–CH_3), 1.24 (3H, m, CH_3), 4.04 (3H, s, OCH_3), 4.66 (1H, brs, CH), 4.78 (1H, d, *J* 11.2 Hz, CH), 5.00 (1H, brs, CH), 5.04 (1H, brs, CH), 6.23 (1H, brs, CH), 6.50 (1H, brs, CH), 6.85 (2H, t, *J* 10.0 Hz, ArCH), 7.03–8.32 (27H, m, ArCH); δ_C ^{13}C NMR (δ, 100 MHz, CD$_2$Cl$_2$); 19.3, 20.1, 20.3, 23.0, 27.6, 30.0, 30.2, 32.3, 51.5, 52.0, 82.1, 84.4, 84.9, 85.2, 86.0, 87.1, 87.6, 89.2, 91.4, 91.7, 93.8, 95.2, 96.3, 97.1, 98.1, 124.7 (Ar), 125.2 (Ar), 125.6 (Ar), 125.9 (Ar), 127.5 (Ar), 127.9 (Ar), 128.2 (Ar), 128.7 (Ar), 129.4 (Ar), 129.5 (Ar), 129.8 (Ar), 129.8 (Ar), 130.1 (Ar), 130.2 (Ar), 130.9 (Ar), 131.4 (Ar), 132.0 (Ar), 133.0 (Ar), 133.3 (Ar), 134.6 (Ar), 134.7 (Ar), 150.3, 151.2, 152.3, 152.3, 153.0, 167.3, 171.9, 176.6; δ_P ^{31}P NMR (δ, 109 MHz, CDCl$_3$); 52.1 (a)–(PPh$_3$), 54.5 (b)–(PPh$_3$); +ve; HRMS; LSIMS; pFAB (NOBA); m/z, calculated for C$_{52}$H$_{44}$O$_4$PCo; [M]$^+$; requires 822.2304, found 822.2307. [Note: The ^{1}H NMR is for the major isomer, some minor isomers peak appear to be broad and overlapping].

C$_{53}$H$_{46}$CoO$_4$P
Mol. Wt.: 836.8369
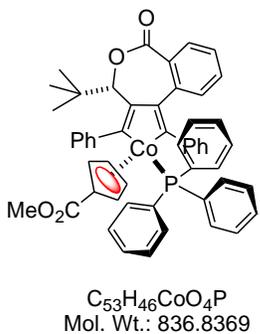
(S_C,R_{Co},P)*–(570).

Using the general procedure in **section 5.7a(ii)**, *rac*–4,4–dimethyl–1–phenylpent–1–yn–3–yl 2–(phenylethynyl)benzoate **(538)** (0.33 g, 0.84 mmol) gave (S_C,R_{Co},P)*–(570) (0.36 g, 51%) as a red crystalline solid after silica gel column chromatography using 3:7 EtOAc/hexane as the elutant solvent mixture. [Note: *d.r.*= 8(a):2(b):1(c)].

(S_C,R_{Co},P)*–(570): m.p. 160–162°C; Anal. Calc. for $C_{53}H_{46}CoO_4P$; Calc.; C, 76.07; H, 5.54; Found; C, 76.12; H, 5.62; IR (thin film) v_{max}; 1717 cm^{-1}; δ_H ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 0.54 (9H, s, (CH_3)$_3$C), 3.71 (3H, s, OCH_3), 4.36 (1H, s, CH), 4.46 (1H, s, CH), 5.00 (1H, brs, CH), 5.99 (1H, s, CH), 6.03 (1H, s, CH), 6.30–7.96 (29H, m, ArCH); δ_C ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 27.2, 36.6, 51.2, 59.3, 82.3, 82.9, 83.5, 83.9, 84.6, 84.7, 84.8, 86.3, 87.2, 88.4, 90.0, 91.8, 93.3, 94.8, 96.9, 97.6, 103.3, 123.3 (Ar), 123.7 (Ar), 124.1 (Ar), 124.2 (Ar), 126.3 (Ar), 126.4 (Ar), 126.5 (Ar), 126.6 (Ar), 126.7 (Ar), 126.8 (Ar), 126.9 (Ar), 127.0 (Ar), 127.1 (Ar), 127.2 (Ar), 127.3 (Ar), 127.4 (Ar), 127.5 (Ar), 127.8 (Ar), 128.3 (Ar), 129.7 (Ar), 129.8 (Ar), 130.4 (Ar), 132.6 (Ar), 132.7 (Ar), 132.9 (Ar), 133.0 (Ar), 133.6 (Ar), 133.8 (Ar), 138.5 (Ar), 149.3 (Ar), 149.7 (Ar), 150.1 (Ar), 152.0, 152.4, 166.0, 170.0, 171.3; δ_P ^{31}P NMR (δ, 162 MHz, CDCl$_3$); 48.0 (c)–(PPh$_3$), 50.0 (a)–(PPh$_3$), 51.9 (b)–(PPh$_3$); +ve; HRMS; LSIMS; pFAB (NOBA); m/z, calculated for $C_{53}H_{46}CoO_4P$; [M]$^+$; requires 836.2460, found 836.2464. [Note: The ^{1}H NMR reports the major isomer, some minor isomer peak appear to be broad and overlapping].

$C_{51}H_{39}CoF_3O_4P$
Mol. Wt.: 862.7551
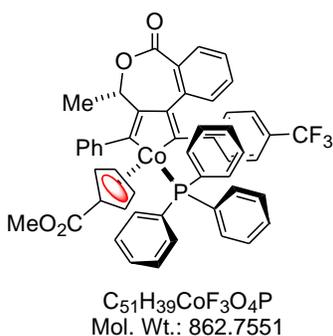
(S_C,R_{Co},P)*–(571).

Using the general procedure in **section 5.7a(ii)**, *rac*–4–phenylbut–3–yn–2–yl 2–((4–(trifluoromethyl)phenyl)ethynyl)benzoate (536) (0.09 g, 0.20 mmol) gave (S_C,R_{Co},P)*–(571) (0.12 g, 68%) as a bright red crystalline solid after silica gel column chromatography using 3:7 EtOAc/hexane as the elutant solvent mixture. [Note: *d.r.*= 9(a):2(b):1.5(c):1(d)].

(S_C,R_{Co},P)*–(571): m.p.170–172°C; IR (thin film) v_{max}; 1695, 1324, 698 cm^{-1}; δ_H ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 0.30 (3H, d, J 6.9 Hz, (d)–CH_3), 0.48 (3H, d, J 7.2 Hz, (b)–CH_3), 1.06 (3H, d, J 7.2 Hz, (a)–CH_3), 1.62 (3H, d, J 7.2 Hz, (c)–CH_3), 3.16 (3H, s, (d)–OCH_3), 3.20 (3H, s, (c)–OCH_3), 3.59 (3H, s, (a)–OCH_3), 4.21 (1H, s, CH), 4.59 (1H, s, CH), 4.95 (1H, q, J 7.2 Hz, (a)–CH), 5.76 (1H, s, CH), 5.86 (1H, s, CH), 6.36 (1H, t, J 8.6 Hz, ArCH), 6.66 (1H, t, J 8.2 Hz, ArCH), 6.76–7.65 (26H, m, ArCH); δ_C ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 19.9 (CH_3), 52.2 (CH), 75.2, 85.6, 85.7, 87.1, 93.5, 94.0, 100.2, 124.1 (Ar), 124.2 (Ar), 125.4 (Ar), 125.7 (Ar), 126.0 (Ar), 126.2 (Ar), 126.7 (Ar), 127.9 (Ar), 128.2 (Ar), 128.7 (Ar), 129.5 (Ar), 130.0 (Ar), 130.1 (Ar), 130.5 (Ar), 131.2 (Ar), 131.3 (Ar), 131.6 (Ar), 132.1 (Ar), 132.7 (Ar), 133.0 (Ar), 133.1 (Ar), 133.2 (Ar), 134.0 (Ar), 134.1 (Ar), 135.2 (Ar), 137.4 (Ar), 137.5 (Ar), 150.4, 152.8, 152.9, 154.6, 167.0, 171.7, 172.6, 172.9, 173.1, 173.3, 173.5; δ_F ^{19}F NMR (δ, 376 MHz, CDCl$_3$); –63.9 (a), –63.8 (c), –63.2 (b), –63.1 (d); δ_P ^{31}P

NMR (δ, 109 MHz, CDCl$_3$); 48.8 (b)–(PPh$_3$), 49.2 (a)–(PPh$_3$), 50.1 (d)–(PPh$_3$), 51.3 (c)–(PPh$_3$); +ve; HRMS; LSIMS; pFAB (NOBA); m/z, calculated for C$_{51}$H$_{39}$CoF$_3$O$_4$P; [M]$^+$; requires 862.1865, found 862.1862.

C$_{51}$H$_{39}$CoF$_3$O$_4$P
Mol. Wt.: 862.7551
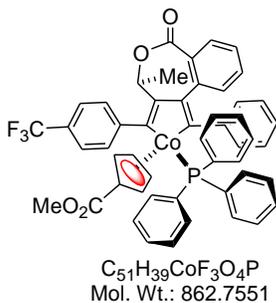
(S_C,R_{Co},P)*–(572).

Using the general procedure in **section 5.7a(ii)**, *rac*–4–(4–(trifluoromethyl)phenyl)but–3–yn–2–yl 2–(phenylethynyl)benzoate **(535)** (0.07g, 0.16 mmol) gave (S_C,R_{Co},P)*–(572) (0.07g, 51%) as a bright red crystalline solid after silica gel column chromatography using 3:7 EtOAc/hexane. [Note: *d.r.*= 10(a):2(b):1(c)].

(S_C,R_{Co},P)*–(572): IR (thin film) ν$_{max}$; 1701, 1323, 733 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 0.54 (3H, d, *J* 6.9 Hz, C*H$_3$*), 0.65 (3H, d, *J* 7.4 Hz, (b)–C*H$_3$*), 1.10 (3H, d, *J* 7.2 Hz, (a)–C*H$_3$*), 3.62 (3H, s, (a)–OC*H$_3$*), 3.76 (b)–OC*H$_3$*), 4.14 (1H, brs, C*H*), 4.82 (1H, brs, C*H*), 4.95 (1H, q, *J* 7.2 Hz, (a)–C*H*), 5.55 (1H, brs, C*H*), 6.11–8.13 (29H, m, ArC*H*, C*H*); δ$_C$ ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 19.9 (*C*H$_3$), 21.0, 52.0 (*C*H), 75.2, 84.9, 85.6, 88.6, 89.6, 92.0, 96.5, 96.6, 124.9 (Ar), 125.6 (Ar), 127.5 (Ar), 127.9 (Ar), 128.0 (Ar), 128.1 (Ar), 128.2 (Ar), 128.6 (Ar), 128.7 (Ar), 129.2 (Ar), 129.4 (Ar), 129.7 (Ar), 129.9 (Ar), 130.3 (Ar), 130.6 (Ar), 130.8 (Ar), 130.9 (Ar), 131.2 (Ar), 131.4 (Ar), 131.7 (Ar), 131.9 (Ar), 132.3 (Ar), 132.4 (Ar), 132.9 (Ar), 133.1 (Ar), 133.6 (Ar), 133.7 (Ar), 134.0 (Ar), 134.3 (Ar), 135.6 (Ar), 136.0 (Ar), 150.5, 150.9, 151.0, 153.9, 155.6, 155.6, 165.6, 165.9, 166.7; δ$_F$ ^{19}F NMR (δ, 376 MHz, CDCl$_3$) –63.0 (b), –63.5 (a); δ$_P$ ^{31}P NMR (δ, 109 MHz, CDCl$_3$); 49.8 (a)–(PPh$_3$), 52.4 (b)–(PPh$_3$); +ve; HRMS; LSIMS; pFAB (NOBA); m/z, calculated for C$_{51}$H$_{39}$CoF$_3$O$_4$P; [M]$^+$; requires 862.1865, found 862.1870.

C$_{48}$H$_{44}$CoO$_4$P
Mol. Wt.: 774.7675
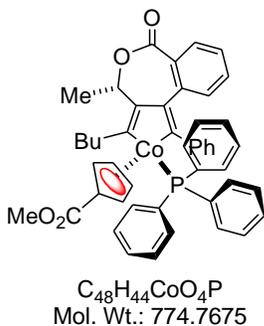
(S_C,R_{Co},P)*–(573).

Using the general procedure in **section 5.7a(ii)**, oct–3–yn–2–yl 2–(phenylethynyl)benzoate **(539)** (0.11 g, 0.34 mmol) gave (S_C,R_{Co},P)*–(573) (0.17g, 65%) as a bright red crystalline solid after silica gel column chromatography using 3:7 EtOAc/hexane. [Note: *d.r.*=4(a):1(b)]

(S_C,R_{Co},P)*–**(573)**: IR (thin film) v_{max}; 2926, 2854, 1717 cm^{-1}; δ_H ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 0.60 (3H, t, J 6.9 Hz, CH_3), 0.70–1.10 (2H, m, CH_2), 1.19 (3H, d, J 7.2 Hz, CH_3), 1.24 (2H, brs, CH_2), 2.24 (1H, t, J 14.8 Hz, CH), 2.52 (1H, t, J 14.8 Hz, CH), 3.62 (3H, s, (a)–OCH_3), 3.70 (3H, s, (b)–OCH_3), 4.37 (1H, s, (b)–CH), 4.45 (1H, s, (a)–CH), 4.84 (1H, s, (a)–CH), 4.94 (1H, s, (b)–CH), 5.48 (1H, q, J 7.2 Hz, CH), 5.57 (1H, s, (a)–CH), 6.07 (1H, s, (a)–CH), 6.41 (2H, brs, ArCH), 6.85–7.59 (22H, m, ArCH); δ_C ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 13.7 (CH$_3$), 19.5 (CH$_2$), 23.6 (CH$_3$), 29.6 (CH$_2$), 32.7 (CH$_2$), 42.2 (CH$_2$), 51.7, 73.3, 87.4, 91.7, 93.0, 93.7, 124.4 (Ar), 124.9 (Ar), 127.5 (Ar), 128.4 (Ar), 129.7 (Ar), 130.4 (Ar), 132.1 (Ar), 132.8 (Ar), 133.2 (Ar), 133.9 (Ar), 136.3 (Ar), 137.8 (Ar), 150.3 (Ar), 151.7 (Ar), 154.2 (Ar), 166.3, 172.2, 173.8, 175.7; ^{31}P NMR (δ, 109 MHz, CDCl$_3$); 51.2 (a)–(PPh$_3$), 52.7 (b)–(PPh$_3$); +ve; HRMS; LSIMS; pFAB (NOBA); m/z, calculated for C$_{48}$H$_{44}$CoO$_4$P; [M]$^+$; requires 774.2304, found 774.2301.

(R_{Co})-**(576)**   (S_{Co})-**(576)**

C$_{48}$H$_{40}$CoO$_2$P
Mol. Wt.: 738.7370
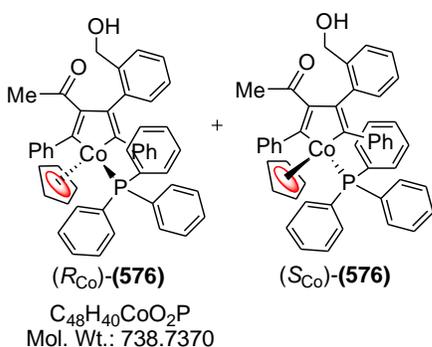
Schlenk tube (100 mL) was charged with (S_C,R_{Co},P)*–**(552)** (0.25 g, 0.34 mmol) and stirred under nitrogen in anhydrous THF (1 mL), cooled to –78°C for 5 mins. DIBAL–H (0.88 mL, 1 M in hexane, 0.88 mmol) was added and reaction mixture stirred for 3 hours before being warmed up to room temp. The reaction mixture was quenched *in situ* with distilled water (0.5 mL) and then extracted with EtOAc (10 mL) and washed with 1 M HCl (10 mL), sat. brine (10 mL) then dried with MgSO$_4$, filtered then purified by silica gel column chromatography using 3:7 EtOAc/petroleum ether 40–60°C to give *rac*–**(576)** (0.11 g, 42%) a red crystalline solid.

Rac–**(576)**: IR (thin film) v_{max}; 3200, 1662, 1434, 722, 697 cm^{-1}; δ_H ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.49 (3H, s, CH_3), 3.90 (1H, brs, OH), 4.14 (1H, d, J 8.1 Hz, CH_2), 4.71 (5H, s, C$_5H_5$), 4.86 (1H, d, J 8.1 Hz, CH_2), 6.12 (1H, d, J 5.0 Hz, ArCH), 6.40 (2H, d, J 5.0 Hz, ArCH), 6.58 (2H, d, J 5.0 Hz, ArCH), 6.70–7.02 (9H, m, ArCH), 7.1–7.64 (15H, m, ArCH); δ_C ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 30.9 (CH$_3$), 64.7 (CH$_2$), 89.8 (C$_5$H$_5$), 124.1 (Ar), 125.1 (Ar), 126.8 (Ar), 126.9 (Ar), 127.6 (Ar), 128.0 (Ar), 128.3 (Ar), 128.5 (Ar), 128.6 (Ar), 129.0 (Ar), 130.0 (Ar), 130.2 (Ar), 131.3 (Ar), 131.9 (Ar), 132.1 (Ar), 132.2 (Ar), 133.6 (Ar), 138.9 (Ar), 141.3 (Ar), 151.8 (Ar), 152.5 (Ar), 153.1 (Ar), 163.9, 166.0, 166.3, 182.3, 182.6; 202.7 (CO); δ_P ^{31}P NMR (δ, 109 MHz, CDCl$_3$); 53.5 (PPh$_3$); +ve; HRMS; LSIMS; pFAB (NOBA); m/z, calculated for C$_{48}$H$_{40}$PCoO$_2$; [M]$^+$; requires 738.2092, found 738.2091.

(pS)-**(578)**   (pR)-**(578)**
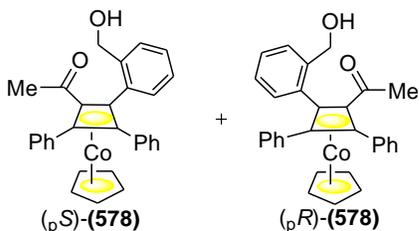
$C_{30}H_{25}CoO_2$
Mol. Wt.: 476.4515

Schlenk tube (100 mL) **(576)** (0.09 g, 0.12 mmol) was heated for 24 hours under an inert nitrogen atmosphere in anhyd. toluene (1 mL). The crude reaction mixture dried under reduced pressure and purified by silica gel column chromatography using 3:7 EtOAc/petroleum ether 40–60°C to give **(578)** (0.056 g, 99%).

(578): m.p. 150–152°C; Anal. Calc. for $C_{30}H_{25}CoO_2$; Calc.; C, 75.63; H, 5.29; Found; C, 75.60; H, 5.35; IR (thin film) v_{max}; 3200, 1700 cm^{-1}; δ_H ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.87 (3H, s, CH_3), 2.10 (1H, brs, OH), 4.32 (1H, d, J 12.0 Hz, CH_2), 4.45 (1H, d, J 12.0 Hz, CH_2), 4.81 (5H, s, C$_5H_5$), 7.00–7.98 (14H, m, ArCH); δ_C ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 27.7 (CH$_3$), 62.2 (CH$_2$) , 77.4 (Cb), 80.9 (2xCb), 82.2 (C$_5$H$_5$), 82.4 (Cb), 126.1 (Ar), 126.3 (Ar), 126.6 (Ar), 126.8 (Ar), 127.1 (Ar), 127.3 (Ar), 127.4 (Ar), 127.5 (Ar), 127.6 (Ar), 128.9 (Ar), 129.7 (Ar), 130.9 (Ar), 131.0 (Ar), 131.1 (Ar), 132.9 (Ar), 133.4 (Ar), 133.9 (Ar), 139.3 (Ar), 202.2 (CO); +ve; HRMS; NESI; pFAB; m/z, calculated for $C_{30}H_{26}CoO_2$; [M+H]$^+$; requires 477.1259, found 477.1252.

$(S_C,R_{Co},P)^*$-**(579)** $(S_C,R_{Co},M)^*$-**(579)**
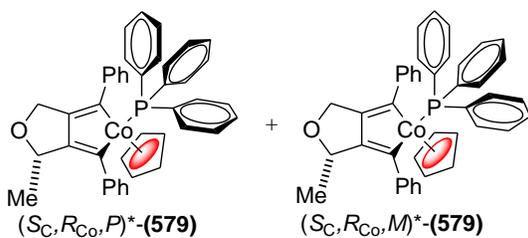
$C_{42}H_{36}CoOP$
Mol. Wt.: 646.6416

Using the general procedure in **section 5.7a**, but using different ratios of starting material *rac*–3–(4–phenylbut–3–yn–2–yloxy)prop–1–ynyl)benzene **(343)** (1.50 g, 5.76 mmol), CoCl(PPh$_3$)$_3$ **(100)** (3.39 g, 5.76 mmol) and sodium η^5–cyclopentadienide (4.00 mL, 8.06 mmol, 2 M in THF) gave complex **(579)** {1.45 g, 39%, *d.r.*= 3 ($S_C,R_{Co},M)^*$: 2 ($S_C,R_{Co},P)^*$} as dark red crystals after silica gel column chromatography using 3:7 EtOAc/petroleum ether 40–60°C as the elutant. [Note: 0.1 g were recrystallised by dissolving in the minimum amount of EtOAc/hexane (*ca.*2:8). This gave clusters of crystals that were 7:1 in favour of ($S_C,R_{Co},M)^*$–**(579)** isomer. A single crystal was used to obtain a crystal structure this had a *d.r.*= 19:1 based on the solution state ^{1}H NMR.

Using the general procedure in **section 5.7a**, *rac*–3–(4–phenylbut–3–yn–2–yloxy)prop–1–ynyl)benzene **(343)** (0.50 g, 1.92 mmol) gave complex **(579)** {0.86 g, 70%, *d.r.*= 2 (S_C, R_{Co}, $M)^*$: 3 (S_C, R_{Co}, $P)^*$} as dark red crystals after silica gel column chromatography using 3:7 EtOAc/petroleum ether 40–60°C. [Note: this sample was re columned using silica gel with decreased polar solvent to 1:19 EtOAc/hexane. However, early and late fractions had *ca. d.r.*= 2:3.

Using the general in procedure **section 5.7b**, *rac*–3–(4–phenylbut–3–yn–2–yloxy)prop–1–ynyl)benzene **(343)** (0.04 g, 0.15 mmol) gave **(579)** as dark red crystals {0.084 g, 87%, *d.r.*=2 (S_C,R_{Co},M)*: 3 (S_C,R_{Co},P)*} after a short filtration through a silica gel pad (2 inches) using hexanes then EtOAc.

(S_C,R_{Co},P)*–**(579)**: m.p. 128–130°C; IR (thin film) ν_{max}; 1482 cm^{-1}; δ_H ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 0.45 (3H, d, *J* 6.2 Hz, CH_3), 4.08–4.15 (2H, m, CH_2), 4.41–4.47 (1H, m, CH), 4.65 (5H, s, C$_5H_5$), 6.60–7.34 (25H, m, ArCH); δ_C ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 20.1 (CH_3), 67.9, 74.4, 74.6, 88.8 (*C$_5$H$_5$*), 124.3 (Ar), 124.4 (Ar), 124.5 (Ar), 127.8 (Ar), 127.9 (Ar), 128.1 (Ar), 128.2 (Ar), 132.4 (Ar), 151.7, 152.6, 160.4, 164.1; δ_P ^{31}P NMR (δ, 109 MHz, CDCl$_3$); 53.2 (*P*Ph$_3$;); +ve; HRMS; NESI; pFAB (NOBA); m/z, calculated for C$_{42}$H$_{34}$OCoP; [M–2H]$^+$; requires 644.1674, found 644.1675.

(S_C,R_{Co},M)*–**(579)**: δ_H ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 0.76 (3H, d, *J* 6.2 Hz, CH_3), 4.08–4.15 (2H, m, CH_2), 4.50 (1H, m, CH), 4.77 (5H, s, C$_5H_5$), 6.60–7.34 (25H, m, ArCH); δ_C ^{13}C NMR (δ, 67 MHz, CDCl$_3$); 20.1 (CH$_3$), 67.5 (CH$_2$), 74.4, 88.1 (*C$_5$H$_5$*), 123.9 (Ar), 124.1 (Ar), 127.0 (Ar), 127.3 (Ar), 127.4 (Ar), 128.3 (Ar), 129.8 (Ar), 133.7 (Ar), 151.6, 151.9, 160.3, 160.4, 163.6; δ_P ^{31}P NMR (δ, 109 MHz, CDCl$_3$); 52.6 (*P*Ph$_3$).

(S_C,R_{Co},P)-**(579)**   (S_C,R_{Co},M)-**(579)**

C$_{42}$H$_{36}$CoOP
Mol. Wt.: 646.6416
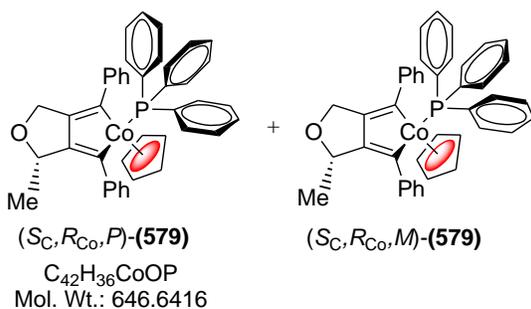
Schlenk tube (100 mL) equipped with stirrer and filled with nitrogen was charged with (S)–(–)–(3–(4–phenyl but–3–yn–2–yloxy)prop–1–ynyl)benzene **(343)** (0.50 g, 1.92 mmol) and (η^5–C$_5$H$_5$)(PPh$_3$)$_2$Co (1.41 g, 2.11 mmol), anhydrous THF (2 mL). The reaction mixture was then heated to 60°C for exactly 30 mins, before the solvent was removed in *vacuo.* The reaction mixture was concentrated and flash chromatography was used to separate the reaction mixture (5% EtOAc/95% petroleum ether 40–60°C) this gave **(579)** (1.34 g, 96%, *ca. d.r.*= 1:1). [Note: *ca.* 100 mg was recrystallised using a 2:8 EtOAc/hexane solvent mixture and gave a *d.r.*= 6:1].

(579); m.p. 160–162°C; ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 0.39 (3H, d, *J* 6.8 Hz, (S_C,R_{Co},P)–CH_3), 0.70 (3H, d, *J* 6.0 Hz, (S_C,R_{Co},M)–CH_3), 4.08–4.15 (2H, m, CH_2), 4.41–4.47 (1H, m, (S_C,R_{Co},P)–CH), 4.50 (1H, m, (S_C,R_{Co},M)–CH), 4.59 (5H, s, (S_C,R_{Co},P)–C$_5H_5$), 4.70 (5H, s, (S_C,R_{Co},M)–C$_5H_5$), 6.60–7.34 (25H, m, ArCH); ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 19.9 ((S_C,R_{Co},P)–CH$_3$), 20.2 ((S_C,R_{Co},M)–CH$_3$), 67.7 (CH$_2$), 74.3 ((S_C,R_{Co},P)–CH), 74.5 ((S_C,R_{Co},M)–CH), 88.2 ((S_C,R_{Co},M)–*C$_5$H$_5$*), 88.6 ((S_C,R_{Co},P)–*C$_5$H$_5$*), 124.1 (Ar), 124.2 (Ar), 127.2 (Ar), 127.3 (Ar), 127.4 (Ar), 127.5 (Ar), 127.6 (Ar), 127.9 (Ar), 128.0 (Ar), 130.0 (Ar), 132.1 (Ar), 132.3 (Ar), 134.0 (Ar), 148.0 (Ar), 148.3 (Ar), 151.6, 151.8, 152.1, 152.4, 160.4, 163.7; δ_P ^{31}P NMR (δ, 122 MHz, CDCl$_3$); 55.0 (S_C,R_{Co},M)–(*P*Ph$_3$), 55.1 (S_C,R_{Co},P)–(*P*Ph$_3$); +ve; LRMS; LSIMS, (xa–fab)

(NOBA); [M]$^+$; m/z, calculated for C$_{42}$H$_{36}$OCoP= 646.2; (S_C,R_{Co},M)–**(579)**, *d.r.*= 6:1, [α]$_D$ = +762.6 (*c* 0.0015, 23.5°C, CHCl$_3$); HPLC (CHIRALCEL OD) 96.5:3.5 hexane/isopropyl alcohol, 1 mL/min R$_t$=22 min 12 secs, (S_C,R_{Co},M)–(+)–**(579)**, R$_t$= 20 min 18 secs, (S_C,R_{Co},P)–(–)–**(579)**.

(S_C,R_{Co},P)*-**(580)**   (S_C,R_{Co},M)*-**(580)**
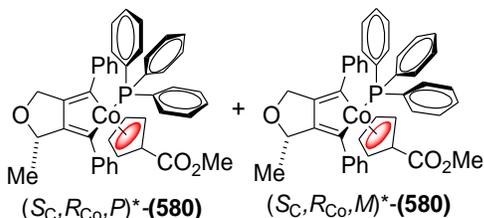
C$_{44}$H$_{38}$CoO$_3$P
Mol. Wt.: 704.6777

Using the general procedure in **section 5.7a(ii)**, *rac*–3–(4–phenylbut–3–yn–2–yloxy)prop–1–ynyl)benzene **(343)** (0.19 g, 0.74 mmol) gave **(580)** (0.13 g, 77%) as a red solid after silica gel column chromatography using 1:19 EtOAc/petroleum ether 40–60°C. [Note: *d.r.*= 2:1].

(580): IR (thin film) ν$_{max}$; 1717 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 270 MHz, CDCl$_3$); 0.31 (3H, d, *J* 6.2 Hz, (major)–CH_3), 0.71 (3H, d, *J* 5.9 Hz, (minor)–CH_3), 3.50 (3H, s, (major)–OCH_3), 3.66 (3H, s, (minor)–OCH_3), 3.97 (1H, m, (minor)–CH), 4.09 (1H, m, (major)–CH), 4.19 (2H, d, *J* 12.4 Hz, (major)–CH_2), 4.32 (1H, m, (minor)–CH), 4.50 (1H, brs, (minor)–CH), 4.55 (2H, brs, (minor)–CH_2), 4.69 (2H, brs, (major)–2xCH), 4.98 (1H, m, (minor)–CH), 5.30 (2H, brs, (major)–2xCH), 5.57 (minor)–CH), 6.85–7.70 (25H, m, ArCH); δ$_C$^{13}C NMR (δ, 67 MHz, CDCl$_3$); 19.5 (major)–CH_3, 20.4 ((minor)–CH$_3$), 51.8, 67.9, 74.0, 74.7, 84.8, 85.8, 88.3, 89.5, 91.6, 92.5, 95.9, 97.4, 100.5, 124.4 (Ar), 124.8 (Ar), 127.3 (Ar), 127.6 (Ar), 127.8 (Ar), 128.0 (Ar), 128.6 (Ar), 130.2 (Ar), 134.2 (Ar), 134.4 (Ar), 150.4, 150.7, 151.1, 151.4, 160.4, 160.8, 164.1, 164.7, 166.9, 167.1 (*CO*); δ$_P$ ^{31}P NMR (δ, 109 MHz, CDCl$_3$); 53.4 (*P*Ph$_3$); +ve; HRMS; LSIMS; pFAB (NOBA); m/z, calculated for C$_{44}$H$_{38}$CoO$_3$P; [M]$^+$; requires 704.1885, found 704.1892.

(*P*)-**(581)**   (*M*)-**(581)**
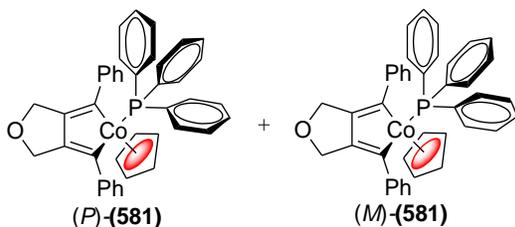
C$_{41}$H$_{34}$CoOP
Mol. Wt.: 632.6150

Conformational propeller isomers of **(581)**.

Using the general procedure in **section 5.7a**, 3,3'–oxybis(prop–1–yne–3,1–diyl)dibenzene **(519)** (0.25 g, 1.02 mmol) gave complex **(581)** (0.22 g, 69%) as a dark brown solid after silica gel column chromatography using 1:19 EtOAc/hexane.

(581): m.p. 148–150°C; Anal. Calc. for C$_{41}$H$_{34}$CoOP·0.2(NaCl); Calc.; C, 76.43; H, 5.32; Found; C, 76.71; H, 5.52; IR (thin film) ν$_{max}$ 1587, 1482, 1434 and 1031 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 3.80 (2H, d, *J* 18.5 Hz, CH_2), 4.22

(2H, d, *J* 18.5 Hz, C*H*$_2$), 5.62 (5H, s, C$_5$*H*$_5$), 6.40–7.80 (25H, m, ArC*H*); δ$_C$ ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 68.4 (*C*H$_2$), 88.1 (*C*$_5$H$_5$), 124.4 (Ar), 127.2 (Ar), 127.8 (Ar), 127.9 (Ar), 128.8 (Ar), 130.1 (Ar), 132.2 (Ar), 134.0 (Ar), 137.5, 148.6, 148.9, 152.4, 160.0; δ$_P$ ^{31}P NMR (δ, 122 MHz, CDCl$_3$); 56.4 (*P*Ph$_3$); HPLC (CHIRALCEL OD) 99:1 hexane/isopropyl alcohol, 0.5 mL/min R$_t$=22 min 6 secs, R$_t$= 38 min 6 secs.

(*R*$_{Co}$,*P*)*-**(582)**   (*S*$_{Co}$,*M*)*-**(582)**   Ar= *p*-FC$_6$H$_4$

C$_{41}$H$_{33}$CoFO
Mol. Wt.: 619.6317
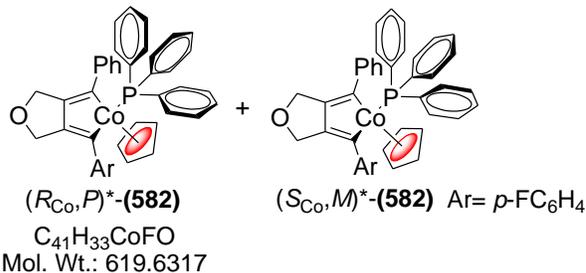
Using the general procedure in **section 5.7a**, 1–fluoro–4–(3–(3–phenylprop–2–ynyloxy)prop–1–ynyl)benzene **(522)** (0.30 g, 1.13 mmol) gave complex **(582)** (0.47 g, 67%, *d.r.*= 4:1) as a dark red solid after silica gel column chromatography using 1:19 EtOAc/petroleum ether 40–60°C.

(582): m.p. 162–164°C; Anal. Calc. for C$_{41}$H$_{33}$CoOF; Calc.; C, 79.47; H, 5.37; Found; C, 79.36; H, 5.43; IR (thin film) v$_{max}$; 1593, 1494, 1435, 1221 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 3.60 (2H, brs, (minor)–C*H*$_2$), 3.82 (2H, brs, (major)–C*H*$_2$), 4.24 (2H, br s, (major)–C*H*$_2$), 4.59 (7H, brs, (minor)–C*H*$_2$, (minor)–C$_5$*H*$_5$) 4.70 (5H, s, (major)–C$_5$*H*$_5$), 6.40–7.80 (24H, m, ArC*H*); δ$_C$^{13}C NMR (δ, 100 MHz, CDCl$_3$); 60.6 ((major)–*C*H$_2$), 60.9 ((minor)–*C*H$_2$), 68.3 ((major)–*C*H$_2$), 85.5 ((minor)–*C*H$_2$), 88.1 ((major)–*C*$_5$H$_5$), 89.4 ((minor)–*C*$_5$H$_5$),114.3 (Ar), 114.5 (Ar), 124.4 (Ar), 127.1 (Ar), 127.8 (Ar), 128.0 (Ar), 128.3 (Ar), 128.7 (Ar), 128.8 (Ar), 130.2 (Ar), 132.2 (Ar), 132.3 (Ar), 133.8 (Ar), 133.9 (Ar), 148.3 (Ar), 152.2, 159.8, 160.3; δ$_P$ ^{31}P NMR (δ, 122 MHz, CDCl$_3$); 56.3 (*P*Ph$_3$); δ$_F$ ^{19}F NMR (δ, 282 MHz, CDCl$_3$); –119.1 (major), –120.1 (minor); HPLC (CHIRALCEL OD) 99:1 hexane/isopropyl alcohol, 0.5 mL/min R$_t$=23 min 0 secs, R$_t$= 30 min 36 secs, R$_t$= 43 min 12 secs.

C$_{10}$H$_{20}$OSi
Mol. Wt.: 184.3507
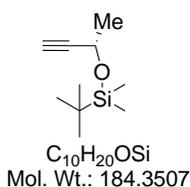
(2*S*)–(–)–2–(*tert*–butyldimethylsilyloxy)but–3–yne, **(585)**.

Compound (*S*)–(–)–**(585)** was synthesised using the literature method [241] using (*S*)–(–)–3–butyn–2–ol **(104)** (0.11 mL, 1.43 mmol) and *tert*–butyldimethylsilyl chloride **(583)** (0.32 g, 2.14 mmol) to give (*S*)–(–)–**(585)** in 92% yield. The NMR data are in agreement with the literature and are given below for information.

(*S*)–(–)–**(585)**: [α]$_D$ = –44.9 (*c* 1.17, 22.8°C,CHCl$_3$); IR (thin film) v$_{max}$; 3312, 2956, 2858, 2115, 1742, 1472, 1253, 1122 and 836 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 0.09 (3H, s, C*H*$_3$), 0.11 (3H, s, C*H*$_3$), 0.90 (9H, s, C(C*H*$_3$)$_3$), 1.41 (3H, d,

J 6.8 Hz, C*H*$_3$), 2.36 (1H, s, C≡C*H*), 4.50 (1H, q, *J* 6.8 Hz, C*H*); δ$_C$ ^{13}C NMR (δ, 100 MHz, CDCl$_3$); –5.0 (*C*H$_3$), –4.7 (*C*H$_3$), 18.2 (*C*H$_3$), 25.8 (C(*C*H$_3$)$_3$), 26.3 (*C*(CH$_3$)$_3$), 58.8 (*C*H), 71.3 (*C*C), 86.4 (*C*C).

C$_{20}$H$_{24}$OSi
Mol. Wt.: 308.4895
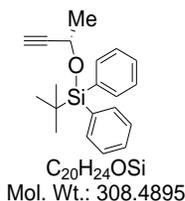
(*S*)–(–)–(But–3–yn–2–yloxy)(*tert*–butyl)diphenylsilane, **(586)**.

Compound (*S*)–(–)–(but–3–yn–2–yloxy)(*tert*–butyl)diphenylsilane **(586)** was prepared from (*S*)–3–butyn–2–ol (0.70 g, 9.93 mmol) and *tert*–butyl diphenylchlorosilane (TBDPSCl) **(584)** (5.17 mL, 19.9 mmol) using the literature method [242] and gave (*S*)–(–)–**(586)** in quantitative yield. The NMR data are in agreement with the literature and are given below for information.

(*S*)–(–)–**(586)**: [α]$_D$ = –71.6 (*c* 0.6, 26.7°C, CHCl$_3$); δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 0.97 (9H, s, C(C*H*$_3$)$_3$), 1.25 (3H, d, *J* 6.4 Hz, C*H*$_3$), 2.15 (1H, d, *J* 2.0 Hz, C*H*), 4.33 (1H, qd, *J* 6.4, 2.0 Hz, C*H*), 7.19–7.28 (6H, m, ArC*H*), 7.56–7.59 (2H, m, ArC*H*), 7.63–7.66 (2H, m, ArC*H*); δ$_c$ ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 19.6 (*C*H$_3$), 25.6 (C(*C*H$_3$)$_3$), 27.3 (C*(*CH$_3$)$_3$), 60.2 (*C*H), 72.1 (*C*C), 86.4 (*C*C), 127.9 (2xAr*C*H), 128.1 (2xAr*C*H), 130.1 (Ar*C*H), 130.2 (Ar*C*H), 133.7 (*C*Ar), 134.0 (*C*Ar), 136.1 (2xAr*C*H), 136.3 (2xAr*C*H); HPLC (CHIRALCEL OD) 99.6:0.4 hexane/isopropyl alcohol, 1 mL/min R$_t$=4 min 18 secs.

C$_{26}$H$_{28}$OSi
Mol. Wt.: 384.5854

(*S*)–(–)–*tert*–Butyldiphenyl(4–phenylbut–3–yn–2–yloxy)silane, **(587)**.

Compound (*S*)–(–)–*tert*–butyldiphenyl(4–phenylbut–3–yn–2–yloxy)silane **(587)** was prepared from (*S*)–(–)–(TBDPS–oxy–but–3–yne **(586)** (1.00 g, 3.24 mmol) and iodobenzene (0.39 mL, 3.56 mmol) using the literature method [243] to give (*S*)–(–)–**(587)** in quantitative yield. The NMR data are in agreement with the literature and are given below for information.

(*S*)–(–)–**(587)**: [α]$_D$ = –183.5 (*c* 0.95, 22.8°C, CHCl$_3$); δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.02 (9H, s, C(C*H*$_3$)$_3$), 1.42 (3H, d, *J* 6.4 Hz, C*H*$_3$), 4.61 (1H, q, *J* 6.4 Hz, C*H*), 7.17–7.18 (5H, m, ArC*H*), 7.27–7.36 (6H, m, ArC*H*), 7.65 (1H, d, *J* 1.2 Hz, ArC*H*), 7.66 (1H, brs, ArC*H*), 7.72 (1H, d, *J* 1.2 Hz, ArC*H*), 7.74 (1H, brs, ArC*H*); δ$_c$ ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 19.5 (*C*H$_3$), 25.5 (C*C*H$_3$), 27.2 (C*(*CH$_3$)$_3$), 60.7 (*C*H), 84.1 (*C*C), 92.0 (*C*C), 123.4 (*C*Ar), 127.8 (2xAr*C*H), 127.9 (2xAr*C*H), 128.3 (Ar*C*H), 128.4 (2xAr*C*H), 129.9 (Ar*C*H), 130.0 (Ar*C*H), 131.8 (2xAr*C*H), 134.0 (*C*Ar), 134.1 (*C*Ar), 136.1 (2xAr*C*H), 136.3 (2xAr*C*H); HPLC (CHIRALCEL OD) 99.6:0.4 hexane/isopropyl alcohol, 1 mL/min R$_t$=4 min 0 secs.
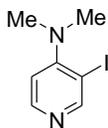
C$_7$H$_9$IN$_2$
Mol. Wt.: 248.0642

(602).

Compound 3–iodo–*N,N*–dimethylpyridin–4–amine **(602)** was prepared from 4–dimethylaminopyridine **(592)** (0.36 g, 3.00 mmol) using the literature method **(210)** and gave **(602)** in 43% yield. The NMR data are in agreement with the literature and are given below for information.

(602): δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 2.96 (6H, s, 2xC*H*$_3$), 6.80 (1H, d, *J* 5.7 Hz, ArC*H*), 8.31 (1H, d, *J* 5.7 Hz, ArC*H*), 8.76 (1H, s, ArC*H*); δ$_c$ ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 43.3 (2xCH$_3$), 89.4 (ArCH), 114.5 (ArCH), 149.7 (ArCH), 159.2 (ArCH), 160.7 (*C*Ar).
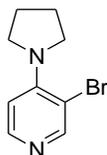
C$_9$H$_{11}$BrN$_2$
Mol. Wt.: 227.1010

(604).

Compound 3–bromo–4–(pyrrolidin–1–yl)pyridine **(604)** was prepared from 4–(1–pyrrolidino)pyridine **(603)** (2.20 g, 14.90 mmol) using the literature method **(211)** and gave **(604)** in 47% yield. The NMR data are in agreement with the literature and are given below for information.

(604): δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.89–1.95 (4H, m, 2xC*H*$_2$), 3.54–3.58 (4H, m, 2xC*H*$_2$), 6.44 (1H, d, *J* 6.0 Hz, ArC*H*), 8.05 (1H, d, *J* 6.0 Hz, ArC*H*), 8.34 (1H, s, ArC*H*); δ$_C$ ^{13}C NMR (δ, 100 MHz, CDCl$_3$); 25.6 (2xCH$_2$), 50.7 (2xCH$_2$), 104.7 (*C*Ar), 110.4 (ArCH), 147.8 (ArCH), 151.1 (*C*Ar), 153.4 (ArCH).
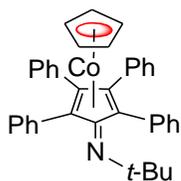
C$_{38}$H$_{29}$CoN
Mol. Wt.: 558.5768
(η^5–Cyclopentadienyl)(η^4–*N*–*tert*–butylimino–*tetra*–phenylcyclopentadiene)cobalt, **(610)**.

Compound **(610)** was synthesised using the literature method **(211)** from metallocyclopentadiene complex **(489a)** (0.10 g, 0.13 mmol) and *tert*–butyl isocyanide **(609)** (0.076 mL, 0.67 mmol) to give **(610)** in 96% yield. The NMR data are in agreement with the literature and are given below for information.

(610): δ$_H$ ^{1}H NMR (δ, 400 MHz, C$_6$D$_6$); 1.28 (9H, s, C(CH_3)$_3$), 4.68 (5H, s, C$_5$H$_5$), 6.80–7.10 (20H, m, ArCH); δ$_C$ ^{13}C NMR (δ, 100 MHz, C$_6$D$_6$); 30.7 {C(CH$_3$)$_3$}, 52.2 (NC), 82.9 (C$_5$H$_5$), 125.6 (CAr), 125.8 (Ar), 126.2 (ArCH), 126.4 (8xArCH), 126.9 (8xArCH), 127.4 (2xArCH), 127.5 (2xArCH), 131.0, 132.7, 132.9, 135.3 (C$_5$N).

C$_{38}$H$_{29}$CoN
Mol. Wt.: 558.5768
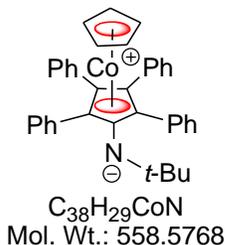
(611).

(611): IR (thin film) v$_{max}$; 1481 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 400 MHz, CD$_3$OD); 1.00 (9H, s, C(CH_3)$_3$), 5.41 (5H, s, C$_5$H$_5$), 6.92–7.46 (20H, m, ArCH); δ$_C$ ^{13}C NMR (δ, 100 MHz, CD$_3$OD); 30.1 {C(CH$_3$)$_3$}, 55.0 (NC), 87.3 (C$_5$H$_5$), 96.5, 123.8 (Ar), 124.2 (Ar), 124.4 (Ar), 127.8 (Ar), 128.6 (Ar), 128.9 (Ar), 129.5, 131.0, 131.6 (C$_5$N).

C$_{39}$H$_{37}$CoIN
Mol. Wt.: 705.5554
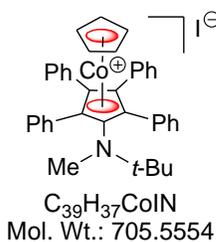
(η^5–Cyclopentadienyl)(η^5–N–*tert*–butyl–N–methylamino–*tetra*phenylcyclopentadienyl)cobaltocenium iodide, **(612)**.

Compound **(612)** was synthesised using the literature method [211] from **(610)** (0.07 g, 0.12 mmol) to give **(612)** in 97% yield. The NMR data are in agreement with the literature and are given below for information.

(612): IR (thin film) v$_{max}$; 3057, 2930, 1630, 1478 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 400 MHz, CD$_3$OD); 1.01 (9H, s, C(CH_3)$_3$), 2.77 (3H, s, CH_3), 5.87 (5H, s, C$_5$H$_5$), 7.00–7.55 (20H, m, ArCH); δ$_C$ ^{13}C NMR (δ, 100 Hz, CD$_3$OD); 29.5 {C(CH$_3$)$_3$}, 42.2 (CH$_3$), 59.6 (NC), 89.6 (C$_5$H$_5$), 97.4 (Ar), 99.3 (Ar), 129.2 (Ar), 129.3 (Ar), 129.7 (Ar), 129.9 (Ar), 130.1 (Ar), 130.6 (Ar), 131.4, 133.1, 133.3 (C$_5$N); +ve; LRMS; ESI; m/z, calculated for C$_{39}$H$_{37}$NCo; [M–I]$^+$= 578.6.

($S_{C,p}S$)*-**(613)**
R= 2,6-(CH$_3$)$_2$C$_6$H$_3$

C$_{33}$H$_{31}$CoF$_6$NOP
Mol. Wt.: 661.5027

($S_{C,p}R$)*-**(613)**
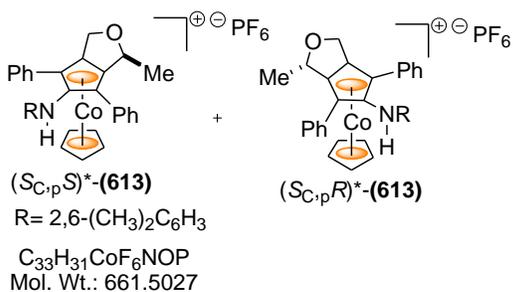
Using the general procedure in **section 5.8**, **(579)** (0.10 g, 0.15 mmol) and 2,6–dimethylphenyl isocyanide (0.08 g, 0.60 mmol), heated 24 hours, HPF$_6$ used as counter ion gave **(613)** (0.09 g, 97%, *d. r.*= 2 ($S_{C,p}S$)*:1 ($S_{C,p}R$)*) as a dark orange solid.

(613): m.p. 200–202°C; Anal. Calc. for C$_{33}$H$_{31}$ONCoPF$_6$; Calc.; C, 59.92; H, 4.72; N, 2.12; Found; C, 59.85; H, 4.63; N, 2.06; IR (thin film) v_{max}; 3500, 2512, 2241,1447 cm^{-1}; δ_H ^{1}H NMR (δ, 400 MHz, CD$_3$OD); 1.31 (3H, d, *J* 6.8 Hz, ($S_{C,p}S$)*–C*H$_3$*), 1.34 (3H, d, *J* 6.8 Hz, ($S_{C,p}R$)*–C*H$_3$*), 1.54 (3H, s, ($S_{C,p}R$)*–C*H$_3$*), 1.63 (3H, s, ($S_{C,p}S$)*–C*H$_3$*), 2.51 (3H, s, ($S_{C,p}R$)*–C*H$_3$*), 2.61 (3H, s, ($S_{C,p}S$)*–C*H$_3$*), 4.70 (1H, d, *J* 13.6 Hz, ($S_{C,p}S$)*–C*H$_2$*), 4.90 (1H, d, *J* 13.6 Hz, ($S_{C,p}S$)*–C*H$_2$*), 5.00 (1H, q, *J* 6.8 Hz, ($S_{C,p}R$)*–C*H*), 5.30 (1H, q, *J* 6.8 Hz, ($S_{C,p}S$)*–C*H*), 5.34 (5H, s, ($S_{C,p}S$)*–C*$_5$H$_5$*), 5,41 (5H, s, ($S_{C,p}R$)*–C*$_5$H$_5$*), 6.22 (1H, d, *J* 8.0 Hz, ($S_{C,p}R$)*–Ar*C*H*), 6.28 (1H, d, *J* 7.6 Hz, ($S_{C,p}S$)*–Ar*C*H*), 6.64–7.93 (12H, m, Ar*CH*); δ_C ^{13}C NMR (δ, 100 Hz, CD$_3$OD); 18.9, 19.2, 29.6, 64.6, 65.6, 73.4, 74.6, 74.9, 76.1, 77.3, 79.8, 85.9 (($S_{C,p}R$)*–C$_5$H$_5$), 87.0 (($S_{C,p}S$)*–C$_5$H$_5$), 99.8 (Ar), 100.3 (Ar), 102.8 (Ar), 105.5 (Ar), 126.3 (Ar), 126.9 (Ar), 127.5 (Ar), 127.9 (Ar), 128.0 (Ar), 128.1 (Ar), 128.2 (Ar), 128.3 (Ar), 128.6 (Ar), 128.8 (Ar), 128.9 (Ar), 129.0 (Ar), 129.1 (Ar), 129.2 (Ar), 129.4 (Ar), 129.5 (Ar), 129.6 (Ar), 129.7 (Ar), 129.9 (Ar), 130.4 (Ar), 131.8 (Ar), 131.9 (Ar), 132.6, 132.9, 133.7, 134.5, 135.0, 135.3, 135.5; +ve; HRMS; HNESP; m/z, calculated for C$_{33}$H$_{31}$CoNO; [M–PF$_6$]$^+$; requires 516.1721, found 516.1732.

(614) R=*t*-Bu
C$_{36}$H$_{36}$CoNO$_2$
Mol. Wt.: 573.6097
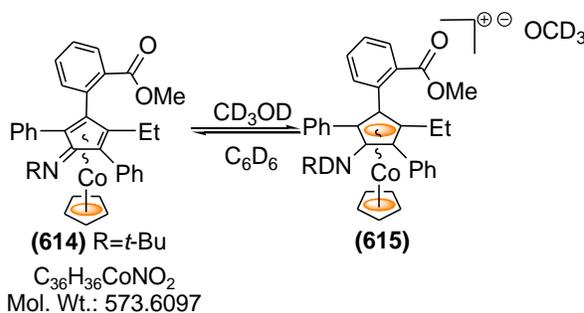
Using the general procedure in **section 5.8**, (S_C,R_{Co},P)*–**(552)** (0.10 g, 0.14 mmol) and *tert*–butyl isocyanide (0.077 mL, 0.68 mmol), heated 72 hours, then purified using silica gel column chromatography 1:9 MeOH/EtOAc to give **(614)** (0.07 g, 83%) as a orange oil.

(615): IR (thin film) v_{max}; 1461 cm^{-1}; δ_H ^{1}H NMR (δ, 400 MHz, CD$_3$OD); 0.71 (3H, t, *J* 7.6 Hz, C*H$_3$*), 0.85 (9H, s, C(C*H$_3$*)$_3$), 1.22 (3H, s, C*H$_3$*,), 2.19 (1H, m, C*H*), 2.35 (1H, m, C*H*), 3.79 (3H, s, OC*H$_3$*), 5.79 (5H, s, C$_5$H$_5$), 7.30 (1H, t, *J* 7.6 Hz, Ar*CH*), 7.39 (1H, d, *J* 7.2 Hz, Ar*CH*), 7.50–7.65 (10H, m, Ar*CH*), 7.78 (1H, t, *J* 8.0 Hz, Ar*CH*), 7.92 (1H, d, *J* 7.6 Hz, Ar*CH*); δ_C ^{13}C NMR (δ,100 Hz, CD$_3$OD); 27.7 (*C*H$_3$), 28.7 (*C*H$_2$), 29.5 (*C*(CH$_3$)$_3$), 52.0 (O*C*H$_3$), 55.1 (N*C*), 86.9 (*C*$_5$H$_5$), 89.1, 91.2, 99.3, 102.9, 128.6 (Ar), 128.7 (Ar), 128.9 (Ar), 129.2 (Ar), 129.5 (Ar), 129.7 (Ar), 130.0 (Ar), 130.7 (Ar), 130.9 (Ar), 131.5 (Ar), 131.8 (Ar), 131.9 (Ar), 132.0 (Ar), 132.6 (Ar), 133.1, 134.6 (*C*$_5$N), 167.0 (*C*O); +ve; HRMS; HNESP; m/z, calculated for C$_{37}$H$_{36}$O$_5$NCo; [M]$^+$; requires 573.2073, found: 573.2067; [M+H]$^+$; requires 574.2151, found 574.2154.

$(S_{C,p}R)^*$-**(618)** $(S_{C,p}S)^*$-**(618)**
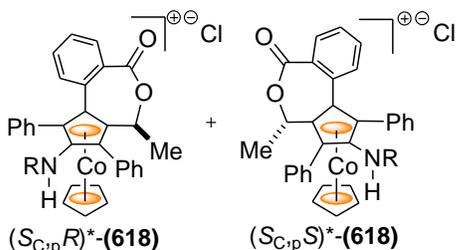
R= 2,6-(CH$_3$)$_2$C$_6$H$_3$

C$_{39}$H$_{33}$ClCoNO$_2$
Mol. Wt.: 42.0710

Using the general procedure in **section 5.8**, $(S_C,R_{Co},P)^*$–**(552)** (0.25 g, 0.34 mmol) and 2,6–dimethylphenyl isocyanide (0.18 g, 1.36 mmol) reaction heated to 70°C for 24 hours (HCl was used to generate the counter ion) this gave **(618)** (0.19 g, 98%, *d.r.*= 2 $(S_{C,p}S)^*$: 1 $(S_{C,p}R)^*$)

(618): m.p. 174–178°C; Anal. Calc. for C$_{39}$H$_{33}$O$_2$NCoCl; Calc.; C, 72.95; H, 5.18; N, 2.18; Found; C, 73.02; H, 5.24; N, 2.11; IR (thin film) v$_{max}$; 1505, 1710 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 400 MHz, CD$_3$OD); 0.87 (3H, d, *J* 6.4 Hz, $(S_{C,p}S)^*$–C*H*$_3$), 1.12 (3H, d, *J* 6.0 Hz, $(S_{C,p}R)^*$–C*H*$_3$), 1.80 (6H, s, rotamers, 2x$(S_{C,p}R)^*$–C*H*$_3$), 2.30 (3H, brs, rotamers, $(S_{C,p}S)^*$–C*H*$_3$), 2.37 (3H, s, $(S_{C,p}S)^*$–C*H*$_3$), 4.34 (1H, q, *J* 6.4 Hz, $(S_{C,p}S)^*$–C*H*), 4.30 (1H, m, $(S_{C,p}R)^*$–C*H*), 5.54 (5H, s, $(S_{C,p}R)^*$–C$_5$*H*$_5$), 5.70 (5H, s, $(S_{C,p}S)^*$–C$_5$*H*$_5$), 6.13–7.77 (17H, m , ArC*H*); δ$_C$ ^{13}C NMR (δ, 100 Hz, CD$_3$OD); 22.5, 51.8, 60.4, 62.9, 72.0, 84.0, 84.3, 86.0, 86.2, 86.4 (($S_{C,p}S)^*$–C$_5$H$_5$), 87.1 (($S_{C,p}R)^*$–C$_5$H$_5$), 87.5, 91.4, 95.2, 98.1, 102.5, 117.8, 126.4 (Ar), 127.0 (Ar), 127.6 (Ar), 127.7 (Ar), 127.8 (Ar), 128.0 (Ar), 128.3 (Ar), 128.4 (Ar), 128.5 (Ar), 128.8 (Ar), 128.9 (Ar), 129.0 (Ar), 129.2 (Ar), 129.3 (Ar), 129.6 (Ar), 129.9 (Ar), 130.3 (Ar), 130.4 (Ar), 130.9 (Ar), 131.0 (Ar), 131.1 (Ar), 131.3 (Ar), 131.4 (Ar), 131.6 (Ar), 131.9 (Ar), 132.0 (Ar), 132.4 (Ar), 132.5 (Ar), 132.7 (Ar), 132.8 (Ar), 134.1 (Ar), 134.7 (Ar), 134.9 (Ar), 135.1 (Ar), 135.3 (Ar), 135.6 (Ar), 136.0 (Ar), 167.1 (($S_{C,p}S)^*$–CO), 169.5 (($S_{C,p}R)^*$–CO); +ve; HRMS; HNESP; m/z, calculated for C$_{39}$H$_{32}$CoNO$_2$; [M–Cl]$^+$; requires 606.1838, found 606.1830. [note: The major diastereoisomer displays rotamers the proportions for this is 2:1].
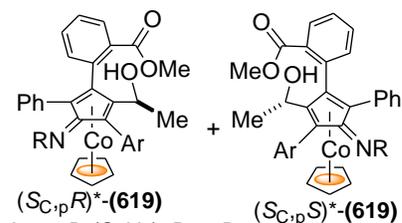
$(S_{C,p}R)^*$-**(619)** $(S_{C,p}S)^*$-**(619)**
Ar= *o*-Br(C$_6$H$_4$), R= *t*-Bu

C$_{36}$H$_{36}$BrCoNO$_3$
Mol. Wt.: 669.5131

Using the general procedure in **section 5.8**, $(S_C,R_{Co},P)^*$–**(566)** (0.20 g, 0.25 mmol), *tert*–butyl isocyanide (0.14 mL, 1.22 mmol) reaction heated 70°C for 50 mins (CH$_3$CO$_2$H, to ring open lactone) to give **(619)** (0.13 g, 85%, *d.r.*= 4 $(S,_pR)^*$: 3 $(S,_pS)^*$) as a orange solid.

(619): m.p 180–182°C; Anal. Calc. for C$_{36}$H$_{36}$O$_3$NCoBr·0.38(CHCl$_3$); Calc.; C, 61.12; H, 5.13; N, 1.96; Found; C, 61.10; H, 5.02; N, 1.85; IR (thin film) v$_{max}$; 1430 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 400 MHz, C$_6$D$_6$); 0.93 (9H, s, $(S_{C,p}R)^*$–C(C*H*$_3$)$_3$), 0.96 (9H,

s, ($S_{C,p}S$)*–C(CH$_3$)$_3$), 1.18 (3H, d, *J* 6.8 Hz, ($S_{C,p}R$)*–CH$_3$), 1.21 (3H, d, *J* 6.8 Hz, ($S_{C,p}S$)*–CH$_3$), 3.49 (3H, s, ($S_{C,p}S$)*–OCH$_3$), 3.52 (3H, s, ($S_{C,p}R$)*–OCH$_3$), 4.39 (1H, q, *J* 6.8 Hz, ($S_{C,p}S$)*–CH), 4.50 (1H, q, *J* 6.8 Hz, ($S_{C,p}R$)*–CH), 5.81 (5H, s, ($S_{C,p}S$)*–C$_5$H$_5$), 5.82 (5H, s, ($S_{C,p}R$)*–C$_5$H$_5$), 7.48–8.32 (13H, m, ArCH), +ve; HRMS; HNESP; m/z, calculated for C$_{36}$H$_{36}$O$_3$NCo^{79}Br; [M+H]$^+$; requires 668.1205, found 668.1203.

($S_{C,p}R$)*-**(620)**   +   ($S_{C,p}S$)*-**(620)**

Ar= *o*-Br(C$_6$H$_4$), R= *t*-Bu
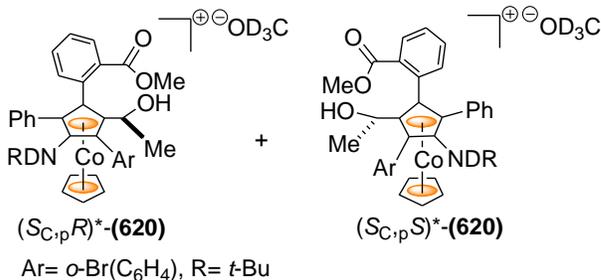
(620): δ$_H$ ^{1}H NMR (δ, 400 MHz, CD$_3$OD); 0.96 (3H, d, *J* 6.8 Hz, ($S_{C,p}S$)*–CH$_3$), 0.97 (3H, d, *J* 6.8 Hz, ($S_{C,p}R$)*–CH$_3$), 1.00 (9H, s, ($S_{C,p}R$)*–C(CH$_3$)$_3$), 1.03 (9H, s, ($S_{C,p}S$)*–C(CH$_3$)$_3$), 3.71 (3H, s, ($S_{C,p}S$)*–OCH$_3$), 3.75 (3H, s, ($S_{C,p}R$)*–OCH$_3$), 4.04 (1H, q, *J* 6.8 Hz, ($S_{C,p}S$)*–CH), 4.20 (1H, q, *J* 6.8 Hz, ($S_{C,p}R$)*–CH), 5.87 (5H, s, ($S_{C,p}S$)*–C$_5$H$_5$), 5.90 (5H, s, ($S_{C,p}R$)*–C$_5$H$_5$), 7.28–8.12 (13H, m, ArCH); δ$_C$ ^{13}C NMR (δ, 100 Hz, CD$_3$OD); 21.3 (($S_{C,p}S$)*–CH$_3$), 21.7 (($S_{C,p}R$)*–CH$_3$), 29.1 (($S_{C,p}S$)*–C(CH$_3$)$_3$), 29.2 ($S_{C,p}R$)*–(C(CH$_3$)$_3$), 51.6, 51.7, 53.9, 54.1, 63.1, 63.3, 83.5, 83.6, , 86.6 (($S_{C,p}R$)*–C$_5$H$_5$), 86.7 (($S_{C,p}S$)*–C$_5$H$_5$), 88.5, 89.0, 100.6 (Ar), 101.4 (Ar), 102.7 (Ar), 123.8 (Ar), 124.5 (Ar), 126.6 (Ar), 128.0 (Ar), 128.5 (Ar), 128.7 (Ar), 128.9 (Ar), 129.3 (Ar), 129.3 (Ar), 129.4 (Ar), 129.9 (Ar), 130.2 (Ar), 130.6 (Ar), 131.3 (Ar), 131.4 (Ar), 131.5 (Ar), 131.5 (Ar), 131.6 (Ar), 131.7 (Ar), 131.8 (Ar), 132.0 (Ar), 132.4 (Ar), 133.2 (Ar), 133.6 (Ar), 134.8 (Ar), 135.1 (Ar), 135.4 (Ar), 136.1 (Ar), 166.8 (CO).
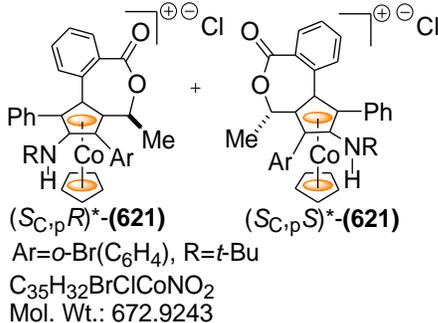
($S_{C,p}R$)*-**(621)**   ($S_{C,p}S$)*-**(621)**

Ar=*o*-Br(C$_6$H$_4$), R=*t*-Bu
C$_{35}$H$_{32}$BrClCoNO$_2$
Mol. Wt.: 672.9243

Using the general procedure in **section 5.8**, (S_C,R_{Co},P)*–**(566)** (0.10 g, 0.12 mmol) and *tert*–butyl isocyanide (0.069 mL, 0.61 mmol) were heated 70°C for 50 mins (HCl was used to generate the counter ion) this gave **(621)** (0.068 g, 84%, *d.r.*= 4 (S,$_p$$R$)*:3 ($S$,$_p$$S$)*).

(621); m.p. 186–188°C; Anal. Calc. for C$_{35}$H$_{32}$O$_2$NCoBrCl; Calc.; C, 62.47; H, 4.79; N, 2.08; Found; C, 62.46; H, 4.86; N, 2.02; IR (thin film) v$_{max}$; 1501, 1710 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 400 MHz, CD$_3$OD); 0.87 (9H, s, ($S_{C,p}S$)*–C(CH$_3$)$_3$), 0.99 (9H, s, ($S_{C,p}R$)*–C(CH$_3$)$_3$), 1.01 (3H, d, *J* 6.8 Hz, ($S_{C,p}S$)*–CH$_3$), 1.47 (3H, d, *J* 7.2 Hz, ($S_{C,p}R$)*–CH$_3$), 4.54 (1H, q, *J* 7.2 Hz, ($S_{C,p}R$)*–CH), 4.57 (1H, m, ($S_{C,p}S$)*–CH), 5.71 (5H, s, ($S_{C,p}S$)*–C$_5$H$_5$), 5.77 (5H, s, ($S_{C,p}R$)*–C$_5$H$_5$), 6.81–8.15 (13H, m, ArCH); δ$_C$ ^{13}C NMR (δ,100 Hz, CD$_3$OD); 21.6 (($S_{C,p}R$)*–CH$_3$), 22.6 (($S_{C,p}S$)*–CH$_3$), 28.7 (C(CH$_3$)$_3$), 54.2 (NC), 70.1,

71.6, 87.7 (($S_{C,p}S$)*,($S_{C,p}R$)*–C_5H_5), 91.5 (Ar), 97.8 (Ar), 125.0 (2xAr), 126.8 (Ar), 127.1 (2xAr), 127.3 (Ar), 127.4 (Ar), 128.5 (Ar), 128.9 (Ar), 129.7 (Ar), 130.2 (Ar), 130.3 (Ar), 130.6 (3xAr), 130.7 (Ar), 130.8 (Ar), 132.3 (Ar), 132.5 (Ar), 132.7 (Ar), 133.3 (2xAr), 133.5 (Ar), 135.5 (2xAr), 163.9 (CO); +ve; HRMS; HNESP; m/z, calculated for C$_{36}$H$_{31}$^{79}BrCoNO$_2$; [M–Cl]$^+$; requires 636.0943, found 636.0945.
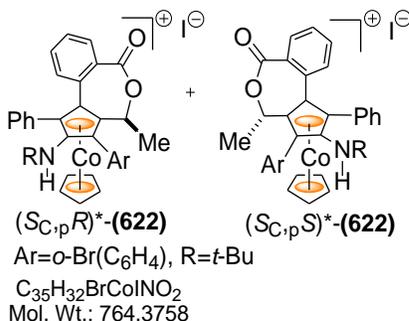
($S_{C,p}R$)*-**(622)**   ($S_{C,p}S$)*-**(622)**
Ar=o-Br(C$_6$H$_4$), R=t-Bu
C$_{35}$H$_{32}$BrCoINO$_2$
Mol. Wt.: 764.3758

Using the general procedure in **section 5.8**, (S_C,R_{Co},P)*–**(566)** (0.10 g, 0.12 mmol) and *tert*–butyl isocyanide (0.069 mL, 0.61 mmol) were heated 70°C for 70 mins. The reaction mixture was then cooled to room temperature and MeI (*ca.*1 mL) was added. The reaction mixture was then stirred for 1.5 hours, and filtered to reveal a orange powder **(622)** (0.094 g, 98%, *d.r.*= 3 (S,$_p$$R$)*: 1 ($S$,$_p$$S$)*).

(622): m.p. 240–242°C; Anal. Calc. for C$_{35}$H$_{32}$O$_2$NCoBrI; Calc.; C, 55.00; H, 4.22; N, 1.83; Found; C, 55.07; H, 4.18; N1.85; IR (thin film) v$_{max}$; 1716, 1506, 1437 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 400 MHz, CD$_3$OD); 0.87 (9H, s, ($S_{C,p}R$)*–C(CH_3)$_3$), 0.99 (9H, s, ($S_{C,p}S$)*–C(CH_3)$_3$), 1.01 (3H, d, *J* 6.4 Hz, ($S_{C,p}R$)*–CH_3), 1.48 (3H, d, *J* 7.2 Hz, ($S_{C,p}S$)*–CH_3), 4.54 (1H, q, *J* 7.2 Hz, ($S_{C,p}S$)*–CH), 5.73 (5H, s, ($S_{C,p}R$)*–C$_5H_5$), 5.78 (5H, s, ($S_{C,p}S$)*–C$_5H_5$), 6.82–8.17 (13H, m, ArCH); δ$_C$ ^{13}C NMR (δ, 100 Hz, CD$_3$OD); 21.6 (($S_{C,p}R$)*–CH_3), 22.6 (($S_{C,p}S$)*–CH_3), 28.7 (C(CH_3)$_3$), 54.2 (NC), 70.1, 71.6, 87.7 (($S_{C,p}S$)*,($S_{C,p}R$)*–C$_5$H$_5$), 91.5 (Ar), 97.8 (Ar), 125.0 (2xAr), 126.8 (Ar), 127.1 (2xAr), 127.3 (Ar), 127.4 (Ar), 128.5 (Ar), 128.9 (Ar), 129.7 (Ar), 130.2 (Ar), 130.3 (Ar), 130.6 (3xAr), 130.7 (Ar), 130.8 (Ar), 132.3 (Ar), 132.5 (Ar), 132.7 (Ar), 133.3 (2xAr), 133.5 (Ar), 135.5 (2xAr), 163.9 (CO); +ve; HRMS; HNESP; m/ z, calculated for C$_{36}$H$_{31}$O$_2$NCo^{79}Br; [M–I]$^+$; requires 636.0943, found 636.0937.

($S_{C,p}R$)*-**(628)**   ($S_{C,p}S$)*-**(628)**
R= 2,6-(CH$_3$)$_2$C$_6$H$_3$
C$_{41}$H$_{37}$ClCoNO$_2$
Mol. Wt.: 670.1242
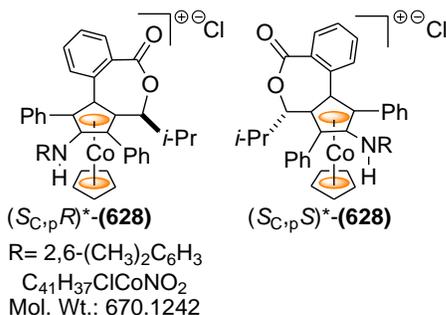
Using the general procedure in **section 5.8**, (S_C,R_{Co},P)*–**(558)** (0.25 g, 0.33 mmol) and 2,6–dimethylphenyl isocyanide (0.18 g, 1.36 mmol) were heated 70°C for 72 hours (HCl was used to generate the counter ion) this gave **(628)** (0.13 g, 60%, *d.r.*= >5 ($S_{C,p}R$)*: 1 ($S_{C,p}S$)*).

(628): m.p. 200–202°C; Anal. Calc. for $C_{41}H_{37}O_2NCoCl$; Calc.; C, 73.95; H, 5.47; N, 2.05; Found; C, 73.88; H, 5.56; N, 2.08; IR (thin film) v_{max}; 1716, 1463, 1261 cm^{-1}; δ_H ^{1}H NMR (δ, 400 MHz, CD$_3$OD); 0.44 (3H, d, *J* 6.8 Hz, minor rotamer, ($S_{C,p}R$)*–C*H*$_3$) 0.60 (3H, d, *J* 6.8 Hz, minor rotamer, ($S_{C,p}R$)*–C*H*$_3$), 0.75 (3H, brs, major rotamer, ($S_{C,p}R$)*–C*H*$_3$), 0.82 (3H, d, *J* 6.4 Hz, major rotamer, ($S_{C,p}R$)*–C*H*$_3$), 1.90 (1H, brs, C*H*), 2.00–2.22 (3H, brs, major rotamer, ($S_{C,p}R$)*–C*H*$_3$), 2.44 (3H, brs, major rotamer, ($S_{C,p}R$)*–C*H*$_3$), 4.02 (1H, d, *J* 7.6 Hz, ($S_{C,p}S$)*–C*H), 5.01 (1H, brs, ($S_{C,p}R$)*–C*H), 5.70 (5H, s, major rotamer, ($S_{C,p}R$)*–C$_5$H$_5$), 5.73 (5H, s, minor rotamer, ($S_{C,p}R$)*–C$_5$H$_5$), 5.75 (5H, s, ($S_{C,p}S$)*–C$_5$H$_5$), 6.20–8.02 (17H, m, ArC*H*); δ_C^{13}C NMR (δ, 100 Hz, CD$_3$OD); 18.7 (minor rotamer, ($S_{C,p}R$)*–2xC*H*$_3$), 18.9 (major rotamer, ($S_{C,p}R$)*–C*H*$_3$), 19.6 (major rotamer, ($S_{C,p}R$)*–C*H*$_3$), 29.4, 29.6, 34.2, 51.6, 72.8, 86.5, 86.9, 87.1 (minor rotamer, ($S_{C,p}R$)*–C$_5$H$_5$), 87.6, 87.7 (major rotamer, ($S_{C,p}R$)*–C$_5$H$_5$), 88.0, 100.7 (Ar), 102.1 (Ar), 126.1 (Ar), 127.0 (Ar), 127.4 (Ar), 127.7 (Ar), 127.8 (Ar), 128.1 (Ar), 128.4 (Ar), 128.8 (Ar), 129.2 (Ar), 130.1 (Ar), 130.8 (Ar), 131.1 (Ar), 131.6 (Ar), 131.8 (Ar), 131.9 (Ar), 132.3 (Ar), 132.4 (Ar), 132.7 (Ar), 132.9 (Ar), 134.8 (Ar), 135.2 (Ar), 135.5 (Ar), 135.9 (Ar), 166.2, 169.3; +ve; HRMS; HNESP; m/z, calculated for $C_{41}H_{36}O_2NCo$; [M–Cl]$^+$; requires 634.2151, found 634.2155. [Note: The major diastereoisomer displays rotamers the proportions for this are 2:1].

($S_{C,p}R$)*-**(629)**
R= 2-CH$_3$,6-Cl-C$_6$H$_3$
$C_{40}H_{34}ClCoF_6NO_2P$
Mol. Wt.: 800.0538
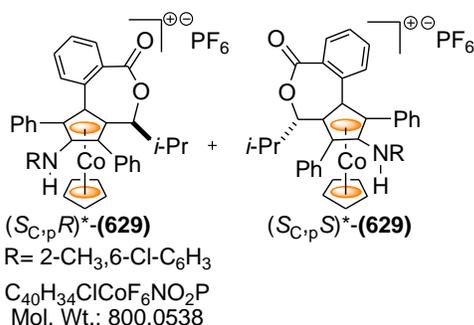
($S_{C,p}S$)*-**(629)**

Using the general procedure in **section 5.8**, (S_C,R_{Co},P)*–**(558)** (0.25 g, 0.33 mmol) and 2–methyl,6–chloro phenylisocyanide (0.19 g, 1.24 mmol) were heated 70°C for 72 hours (HPF$_6$ was used to generate the counter ion) this gave **(629)** (0.16 g, 65%, *d.r.*= 5 ($S_{C,p}R$)*:1 ($S_{C,p}S$)*).

(629): m.p. 280–282°C; Anal. Calc. for $C_{40}H_{34}O_2NCoClPF_6$; Calc.; C, 60.05; H, 4.28; N, 1.75; Found; C, 60.14; H, 4.17; N, 1.76; IR (thin film) v_{max}; 1700, 1520, 1460 cm^{-1}; δ_H ^{1}H NMR (δ, 400 MHz, CD$_3$OD, 20°C); 0.77 (3H, d, *J* 6.4 Hz, ($S_{C,p}R$)*–C*H*$_3$), 0.88 (3H, d, *J* 6.4 Hz, C*H*$_3$), 0.93 (3H, d, *J* 6.0 Hz, ($S_{C,p}S$)*–C*H*$_3$), 1.65 (1H, brs, ($S_{C,p}R$)*–C*H), 2.32 (3H, brs, C*H*$_3$), 4.99 (1H, brs, C*H*), 5.57 (5H, s, major rotamer, ($S_{C,p}R$)*–C$_5$H$_5$), 5.63 (5H, s, minor rotamer, ($S_{C,p}R$)*–C$_5$H$_5$), 5.64 (5H, s, major rotamer, ($S_{C,p}S$)*–C$_5$H$_5$), 5.70 (5H, s, minor rotamer ($S_{C,p}S$)*–C$_5$H$_5$), 6.20–8.02 (17H, m, ArC*H*); δ_C^{13}C NMR (δ, 100 Hz, CD$_3$OD); 18.6 (($S_{C,p}R$)*–C*H*$_3$), 19.5 (($S_{C,p}S$)*–C*H*$_3$), 20.0 (($S_{C,p}R$)*–C*H*$_3$), 29.4, 87.6 (major+minor rotamer, ($S_{C,p}S$)*–C$_5$H$_5$), 87.8 (major+minor rotamer, ($S_{C,p}R$)*–C$_5$H$_5$), 126.4 (Ar), 127.0 (Ar), 127.2 (Ar), 127.3 (Ar), 127.7 (Ar), 128.0 (Ar), 128.7 (Ar), 129.3 (Ar), 130.1 (Ar), 130.4 (Ar), 130.8 (Ar), 131.0 (Ar), 131.4 (Ar), 132.2 (Ar), 132.4 (Ar), 132.6 (Ar), 137.1 (Ar), 169.3 (CO). [Note: The major diastereoisomer of ($S_{C,p}R$) displays rotamers the

proportions for this are 2:1]. δ_P ^{31}P NMR (δ, 121 MHz, CD$_3$OD); –144.54 (*septet*); δ_F ^{19}F NMR (δ, 282 MHz, CD$_3$OD); –73.7 (d); +ve; HRMS; HNESP; m/z, calculated for C$_{40}$H$_{34}$O$_2$N^{35}ClCo; [M–PF$_6$]$^+$; requires 654.1597, found 654.1605.

($S_{C,p}R$)*-**(630)**   ($S_{C,p}S$)*-**(630)**

Ar=*o*-BrC$_6$H$_5$, R= 2,6-(CH$_3$)$_2$,C$_6$H$_3$
C$_{39}$H$_{32}$BrClCoNO$_2$
Mol. Wt.: 720.9671
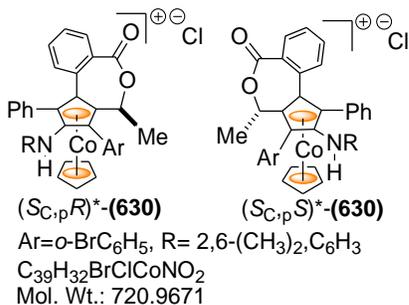
Using the general procedure in **section 5.8**, (S_C,R_{Co},P)*–**(566)** (0.25 g, 0.31 mmol) and 2,6–dimethylphenylisocyanide (0.16 g, 1.24 mmol) 70°C for 70 mins (HCl was used to generate the counter ion) this gave **(630)** (0.20 g, 97%, *d.r.*= 2 ($S_{C,p}S$)*:1 ($S_{C,p}R$)*) as a dark orange solid.

(630): m.p. 208–210°C; Anal. Calc. for C$_{39}$H$_{32}$O$_2$NCoBrCl; Calc.; C, 64.97; H, 4.47; N, 1.94; Found; C, 64.86; H, 4.56; N, 1.89; IR (thin film) ν$_{max}$; 1530, 1710 cm^{-1}; δ_H ^1H NMR (δ, 400 MHz, CD$_3$OD); 0.95 (3H, d, *J* 6.4 Hz, major rotamer, ($S_{C,p}S$)*–C*H$_3$), 1.18 (3H, d, *J* 6.4 Hz, minor rotamer, ($S_{C,p}S$)*–C*H$_3$), 1.55 (3H, d, *J* 7.2 Hz, ($S_{C,p}R$)*–C*H$_3$), 1.80–1.90 (6H, m, ($S_{C,p}R$)*–(2xC*H$_3$)), 2.38–2.50 (6H, m, ($S_{C,p}S$)*–(2xC*H$_3$)), 4.13 (1H, q, *J* 6.4 Hz, ($S_{C,p}S$)*–C*H), 4.23 (1H, m, ($S_{C,p}R$)*–C*H), 5.70 (5H, s, ($S_{C,p}R$)*–C*H$_5$), 5.79 (5H, s, minor rotamer ($S_{C,p}S$)*–C*H$_5$), 5.81 (5H, s, major rotamer ($S_{C,p}S$)*–C*H$_5$), 6.17–8.10 (16H, m, ArC*H*); δ_C ^{13}C NMR (δ, 100 Hz, CD$_3$OD); 21.9, 22.1, 29.6, 52.0, 62.9, 63.1, 70.1, 71.5, 82.4, 82.6, 83.4, 86.1 (minor rotamer, ($S_{C,p}R$)*–C$_5$H$_5$), 86.2 (major rotamer, ($S_{C,p}R$)*–C$_5$H$_5$), 87.2 (major rotamer, ($S_{C,p}S$)*–C$_5$H$_5$), 87.4 (minor rotamer, ($S_{C,p}S$)*–C$_5$H$_5$), 91.9, 92.0, 94.8, 96.9, 100.9, 101.0, 103.0, 125.3 (Ar), 125.6 (Ar), 125.9 (Ar), 126.0 (Ar), 126.5 (Ar), 126.6 (Ar), 127.1 (Ar), 127.2 (Ar), 127.3 (Ar), 127.4 (Ar), 127.5 (Ar), 127.6 (Ar), 127.9 (Ar), 128.1 (Ar), 128.2 (Ar), 128.4 (Ar), 128.6 (Ar), 128.7 (Ar), 128.8 (Ar), 128.9 (Ar), 129.0 (Ar), 129.2 (Ar), 129.4 (Ar), 130.1 (Ar), 130.3 (Ar), 130.4 (Ar), 130.9 (Ar), 131.1 (Ar), 131.2 (Ar), 131.4 (Ar), 131.5 (Ar), 131.9 (Ar), 132.1 (Ar), 132.3 (Ar), 132.4 (Ar), 132.5 (Ar), 132.7 (Ar), 132.9 (Ar), 133.5 (Ar), 133.6 (Ar), 133.7 (Ar), 134.1 (Ar), 134.2 (Ar), 134.6 (Ar), 134.8 (Ar), 135.1 (Ar), 135.5 (Ar), 135.6 (Ar), 135.9 (Ar), 136.0 (Ar), 136.2 (Ar), 167.3, 168.4, 169.5; +ve; HRMS; HNESP; m/z, calculated for C$_{39}$H$_{32}$O$_2$NCo^{79}Br; [M–Cl]$^+$; requires 683.0943, found 683.0945. [Note: The major planar chiral diastereoisomer ($S_{C,p}S$) displays rotamers the proportions for this is *ca.* 3:2]

($S_{C,p}R$)*-**(631)**   ($S_{C,p}S$)*-**(631)**

Ar=*o*-BrC$_6$H$_5$, R= 2-CH$_3$,6-ClC$_6$H$_3$
C$_{38}$H$_{29}$BrClCoF$_6$NO$_2$P
Mol. Wt.: 850.8967

Using the general procedure in **section 5.8**, (S_C,R_{Co},P)*–**(566)** (0.25 g, 0.31 mmol) and 2–methyl,6–chloro phenylisocyanide (0.19 g, 1.24 mmol) were heated 70°C for 70 min (HPF$_6$ was used to generate the counter ion) this gave **(631)** (0.22 g, 84%, *d.r.= ca.* 2 (S_C,$_p$S)*:1 (S_C,$_p$R)*).

(631): m.p. 270–272°C, IR (thin film) v$_{max}$; 1710, 1521; Anal. Calc. for C$_{38}$H$_{29}$O$_2$NCoClBrPF$_6$; Calc.; C, 53.70; H, 3.32; N, 1.65; Found; C, 53.76; H, 3.31; N, 1.58; δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.24 (3H, d, *J* 6.8 Hz, (S_C,$_p$R)*–C*H$_3$*), 1.56 (3H, d, *J* 7.2 Hz, (S_C,$_p$S)*–C*H$_3$*), 1.70 (3H, s, (S_C,$_p$S)*–C*H$_3$*), 2.39 (3H, brs, minor rotamer, (S_C,$_p$R)*–C*H$_3$*), 2.40 (3H, brs, (S_C,$_p$R)*–C*H$_3$*), 4.80 (1H, m, C*H*), 5.49 (5H, s, (S_C,$_p$R)*– C$_5$*H$_5$*), 5.57 (5H, s, (S_C,$_p$R)*– C$_5$*H$_5$*), 5.64 (5H, s, (S_C,$_p$S)*–C$_5$*H$_5$*), 6.55–8.07 (16H, m, ArC*H*); δ$_C$ ^{13}C NMR (δ, 100 Hz, CD$_3$OD); 22.7, 23.3, 29.5, 29.9, 52.6, 52.8, 53.9, 54.7, 63.5, 69.6, 69.7, 71.8, 84.9, 85.1, 85.5, 85.9, 87.2 ((S_C,$_p$S)*–C$_5$H$_5$), 87.7 (minor rotamer, (S_C,$_p$R)*–C$_5$H$_5$), 87.9 (major rotamer, (S_C,$_p$R)*–C$_5$H$_5$), 88.1, 88.3, 91.7, 92.1, 94.9, 95.1, 95.7, 98.3, 102.5, 118.4, 119.1, 120.6 (Ar), 121.8 (Ar), 123.2 (Ar), 124.0 (Ar) 125.9 (Ar), 126.2 (Ar), 126.4 (Ar), 126.5 (Ar), 126.7 (Ar), 126.9 (Ar), 127.0 (Ar), 127.1 (Ar), 127.3 (Ar), 127.4 (Ar), 127.5 (Ar), 127.9 (Ar), 128.1 (Ar), 128.4 (Ar), 128.7 (Ar), 128.8 (Ar), 128.9 (Ar), 129.1 (Ar), 129.3 (Ar), 129.4 (Ar), 129.6 (Ar), 129.8 (Ar), 129.9 (Ar), 130.0 (Ar), 130.1 (Ar), 130.4 (Ar), 130.5 (Ar), 130.7 (Ar), 131.0 (Ar), 131.2 (Ar), 131.9 (Ar), 132.1 (Ar), 132.2 (Ar), 132.6 (Ar), 132.7 (Ar), 132.8 (Ar), 133.1 (Ar), 133.2 (Ar), 133.4 (Ar), 133.6 (Ar), 134.7 (Ar), 136.5 (Ar), 136.8 (Ar), 137.1 (Ar), 138.0 (Ar), 141.4 (Ar), 167.3, 168.3, 169.5; +ve; HRMS; HNESP; m/z, calculated for C$_{38}$H$_{28}$O$_2$NCo^{79}Br^{35}Cl; [M–PF$_6$]$^+$; requires 704.0397, found 704.0393. [Note: The major planar chiral diastereoisomer (S_C,$_p$R) displays rotamers the proportions for this is *ca.* 4:1].

(S_C,$_p$R)*-**(633)**
R= 2-CH$_3$,6-ClC$_6$H$_3$
C$_{38}$H$_{30}$ClCoF$_6$NO$_2$P
Mol. Wt.: 772.0007

(S_C,$_p$S)*-**(633)**
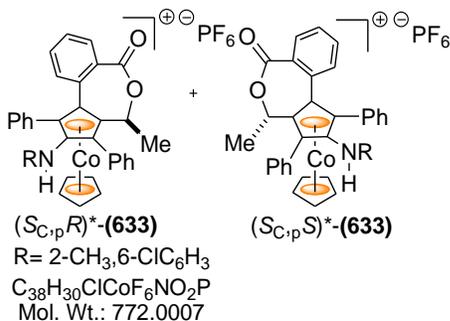
Using the general procedure in **section 5.8**, (S_C,R_{Co},P)*–**(552)** (0.25 g, 0.34 mmol) and 2–methyl,6–chloro phenyl isocyanide (0.19 g, 1.24 mmol) and reaction heated 24 hours (HPF$_6$ was used to generate the counter ion) this gave **(633)** (0.23 g, 92%, *d.r.*= 2 (S_C,$_p$S)*:1 (S_C,$_p$R)*) as a dark orange solid.

(633): m.p. 208–210°C; Anal. Calc. for C$_{38}$H$_{30}$O$_2$NCoClPF$_6$; Calc.; C, 59.12; H, 3.92; N, 1.81; Found; C, 58.99; H, 3.93; N, 1.74; IR (thin film) v$_{max}$; 1520, 1710 cm^{-1}; δ$_H$ ^{1}H NMR (δ, 400 MHz, CDCl$_3$); 1.40 (3H, brs, (S_C,$_p$S)*–C*H$_3$*), 1.50 (3H, brs, (S_C,$_p$R)*–C*H$_3$*), 1.80–2.20 (3H, m, (S_C,$_p$S)*,(S_C,$_p$R)*–C*H$_3$*), 4.60 (1H, brs, (S_C,$_p$R)*,(S_C,$_p$R)*–C*H*), 5.50 (5H, s, minor rotamer, (S_C,$_p$R)*–C$_5$*H$_5$*), 5.53 (5H, s, major rotamer, (S_C,$_p$R)*–C$_5$*H$_5$*), 5.62 (5H, brs, (S_C,$_p$S)*–C$_5$*H$_5$*), 6.30–7.99 (17H, m, ArC*H*); δ$_C$^{13}C NMR (δ, 100 Hz, CDCl$_3$); 22.7 ((S_C,$_p$R)*–C*H$_3$*), 23.3 ((S_C,$_p$S)*–C*H$_3$*), 29.5, 28.8, 52.6, 52.8, 53.9, 54.6, 54.7, 63.5, 69.6, 69.7, 71.8, 85.1, 85.5, 87.2 ((S_C,$_p$S)*–C$_5$H$_5$), 87.7 (minor rotamer, (S_C,$_p$R)*–C$_5$H$_5$), 87.9 (major rotamer,

$(S_{C,p}R)^*$–C_5H_5), 88.1, 88.3, 91.7, 98.3, 102.5 (Ar), 118.4 (Ar), 119.1 (Ar), 120.6 (Ar), 123.7 (Ar), 126.4 (Ar), 126.5 (Ar), 126.7 (Ar), 127.0 (Ar), 127.3 (Ar), 127.4 (Ar), 127.9 (Ar), 128.4 (Ar), 128.8 (Ar), 128.9 (Ar), 128.9 (Ar), 129.1 (Ar), 129.3 (Ar), 129.4 (Ar), 129.8 (Ar), 129.9 (Ar), 130.0 (Ar), 130.4 (Ar), 130.5 (Ar), 131.0 (Ar), 131.0 (Ar), 131.2 (Ar), 131.9 (Ar), 132.1 (Ar), 132.2 (Ar), 132.6 (Ar), 132.7 (Ar), 132.8 (Ar), 133.4 (Ar), 133.6 (Ar), 134.7 (Ar), 136.8 (Ar), 137.1 (Ar), 141.4 (Ar), 167.0, 168.0, 170.0; +ve; HRMS; HNESP; m/z, calculated for $C_{38}H_{30}O_2NCo^{35}Cl$; $[M–PF_6]^+$; requires 626.1292, found 626.1292. [Note: The minor planar chiral diastereoisomer $(S_{C,p}R)^*$ displays rotamers the proportions for this is *ca.* 4:1].

$(S_{C,p}R)$-**(634)** $(S_{C,p}S)$-**(634)**

R= 2,6-$(CH_3)_2C_6H_3$

$C_{39}H_{33}CoF_6NO_2P$
Mol. Wt.: 751.5822
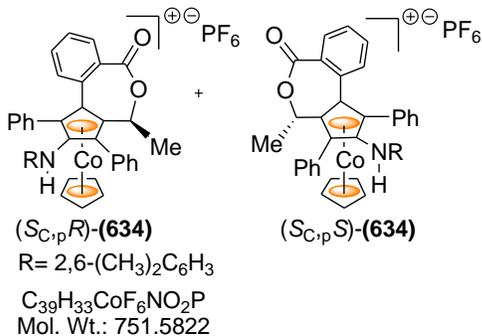
Using the general procedure in **section 5.8**, (S_C,R_{Co},P)–**(552)** (0.25 g, 0.34 mmol) and 2,6–dimethylphenylisocyanide (0.18 g, 1.36 mmol) was heated to 70°C for 24 hours (HPF_6 was used to generate the counter ion) this gave **(634)** (0.22 g, 92%, *d.r.*= 2 $(S_{C,p}S)$:1 $(S_{C,p}R)$) as a dark orange solid.
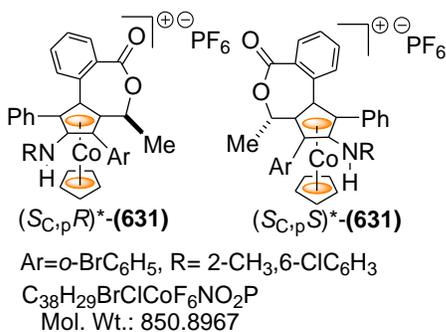
(634): m.p. 178–182°C; $[\alpha]_D$ = –15.11 (*c* 0.0045, 23.7°C, CH_2Cl_2); IR (thin film) v_{max}; 1505, 1710 cm^{-1}; Anal. Calc. for $C_{39}H_{33}O_2NCoPF_6$; Calc.; C, 62.32; H, 4.43; N, 1.86; Found; C, 62.23; H, 4.51; N, 1.90; δ_H ^1H NMR (δ, 400 MHz, CD_3OD); 1.06 (3H, d, *J* 6.8 Hz, $(S_{C,p}S)$–CH_3), 1.11 (3H, d, *J* 6.4 Hz, $(S_{C,p}R)$–CH_3), 1.67–1.74 (3H, s, major rotamer, $(S_{C,p}R)$–CH_3), 1.74 (3H, s, minor rotamer, $(S_{C,p}R)$–CH_3), 1.99 (3H, s, $(S_{C,p}R)$–CH_3), 2.45 (3H, brs, minor rotamer, $(S_{C,p}S)$–CH_3), 2.50 (3H, s, major rotamer, $(S_{C,p}S)$–CH_3), 2.56 (3H, s, $(S_{C,p}S)$–CH_3), 4.47 (1H, q, *J* 6.4 Hz, $(S_{C,p}R)$–C*H*), 4.52 (1H, q, *J* 6.8 Hz, $(S_{C,p}S)$–C*H*), 5.73 (5H, s, $(S_{C,p}R)$–C_5H_5), 5.81 (5H, s, major rotamer, $(S_{C,p}S)$–C_5H_5), 5.82 (5H, s, minor rotamer, $(S_{C,p}S)$–C_5H_5), 6.34–8.02 (17H, m , ArC*H*); δ_C ^{13}C NMR (100 Hz, CD_3OD); 21.8 ($(S_{C,p}R)$–CH_3), 22.5 ($(S_{C,p}S)$–CH_3), 51.8, 63.0, 71.9, 84.3, 86.4 ($(S_{C,p}S)$–C_5H_5), 87.0 ($(S_{C,p}R)$–C_5H_5), 87.5, 97.8, 99.6, 102.5 (Ar), 126.3 (Ar), 127.0 (Ar), 127.2 (Ar), 127.5 (Ar), 127.6 (Ar), 127.7 (Ar), 127.9 (Ar), 128.0 (Ar), 128.3 (Ar), 128.4 (Ar), 128.5 (Ar), 128.8 (Ar), 128.9 (Ar), 129.0 (Ar), 129.2 (Ar), 129.3 (Ar), 129.9 (Ar), 130.0 (Ar), 130.3 (Ar), 130.4 (Ar), 130.8 (Ar), 131.0 (Ar), 131.6 (Ar), 131.8 (Ar), 131.9 (Ar), 132.1 (Ar), 132.2 (Ar), 132.4 (Ar), 132.5 (Ar), 132.7 (Ar), 132.8 (Ar), 134.4 (Ar), 134.6 (Ar), 135.0 (Ar), 135.1 (Ar), 135.2 (Ar), 135.6 (Ar), 136.0 (Ar), 167.0, 167.2, 169.7; +ve; HRMS; HNESP; m/z, calculated for $C_{39}H_{33}O_2NCo$; $[M–PF_6]^+$; requires 606.1838, found 606.1828. [Note: The major planar chiral diastereoisomer $(S_{C,p}S)$ displays rotamers the proportions for this is *ca.* 4:1].

Chapter Six

6.0 Bibliography.

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Appendix 1.

Identification code	(S,S)*–(436) [QMULJA295]	
Empirical formula	$C_{20}H_{10}Co_4O_{13}$	
Formula weight	694.0	
Temperature	120(2) K	
Wavelength	0.71073 Å	
Crystal system	Triclinic	
Space group	P1	
Unit cell dimensions	a = 9.34300(10) Å	α = 100.5370(10)°
	b = 11.0123(2) Å	β = 99.4800(10)°
	c = 12.8211(2) Å	γ = 105.4960(10)°
Volume	1217.58(3) Å^3	
Z	2	
Density (calculated)	1.893 Mg/m^3	
Absorption coefficient	2.743 mm^{-1}	
F(000)	684	
Crystal size	0.42 x 0.34 x 0.18 mm^3	
Theta range for data collection	3.43 to 27.53°.	
Index ranges	$-12<=h<=12, -14<=k<=14, -16<=l<=16$	
Reflections collected	26154	
Independent reflections	5585 [R(int) = 0.0385]	
Completeness to theta = 27.53°	99.5%	
Max. and min. transmission	0.6380 and 0.3921	
Refinement method	Full–matrix least–squares on F^2	
Data / restraints / parameters	5585 / 0 / 336	
Goodness–of–fit on F^2	1.018	
Final R indices [I>2sigma(I)]	R1 = 0.0266, wR2 = 0.0603	
R indices (all data)	R1 = 0.0349, wR2 = 0.0639	
Largest diff. peak and hole	0.341 and –0.484 e.Å^{-3}	

Appendix 2.

Identification code	(R, R)*–(437) [QMULJA333]	
Empirical formula	$C_{32}H_{18}Co_4O_{13}$	
Formula weight	846.2	
Temperature	120(2) K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group	P2$_1$/c	
Unit cell dimensions	a = 8.3976(3) Å	α = 90°
	b = 14.8894(6) Å	β = 91.383(2)°
	c = 27.1782(10) Å	γ = 90°
Volume	3397.2(2) Å^3	
Z	4	
Density (calculated)	1.654 Mg/m^3	
Absorption coefficient	1.983 mm^{-1}	
F(000)	1688	
Crystal size	0.15 x 0.12 x 0.11 mm^3	
Theta range for data collection	3.00 to 27.55°.	
Index ranges	$-10<=h<=10, -19<=k<=19, -35<=l<=32$	
Reflections collected	32281	
Independent reflections	7675 [R(int) = 0.0740]	
Completeness to theta = 27.55°	97.9%	
Max. and min. transmission	0.8114 and 0.7552	
Refinement method	Full–matrix least–squares on F^2	
Data / restraints / parameters	7675 / 0 / 420	
Goodness–of–fit on F^2	1.004	
Final R indices [I>2sigma(I)]	R1 = 0.0501, wR2 = 0.0822	
R indices (all data)	R1 = 0.0934, wR2 = 0.0943	
Largest diff. peak and hole	0.797 and –0.412 e.Å^{-3}	

Appendix 3.

Identification code	$(S, S)^*$–(**446**) [QMULJA334]	
Empirical formula	$C_{42}H_{22}Co_4O_{12}$	
Formula weight	954.32	
Temperature	120(2) K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group	$P2_1/n$	
Unit cell dimensions	a = 13.2669(3) Å	$\alpha = 90°$
	b = 14.6959(3) Å	$\beta = 105.2790(10)°$
	c = 20.7234(4) Å	$\gamma = 90°$
Volume	3897.61(14) Å^3	
Z	4	
Density (calculated)	1.626 Mg/m^3	
Absorption coefficient	1.737 mm^{-1}	
F(000)	1912	
Crystal size	0.20 x 0.12 x 0.08 mm^3	
Theta range for data collection	3.05 to 27.55°.	
Index ranges	$-17<=h<=17, -18<=k<=19, -26<=l<=26$	
Reflections collected	36642	
Independent reflections	8887 [R(int) = 0.0609]	
Completeness to theta = 27.55°	98.8%	
Max. and min. transmission	0.8735 and 0.7226	
Refinement method	Full–matrix least–squares on F^2	
Data / restraints / parameters	8887 / 0 / 475	
Goodness–of–fit on F^2	1.093	
Final R indices [I>2sigma(I)]	R1 = 0.0577, wR2 = 0.1034	
R indices (all data)	R1 = 0.0848, wR2 = 0.1162	
Largest diff. peak and hole	0.533 and –0.515 e.Å^{-3}	

Appendix 4.

Identification code	(**489a**) [QMULJA347]	
Empirical formula	$C_{51}H_{40}CoP$	
Formula weight	742.7	
Temperature	120(2) K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group	$P 2_1$	
Unit cell dimensions	a = 10.0702(3) Å	$\alpha = 90°$
	b = 18.5949(4) Å	$\beta = 100.001(2)°$
	c = 10.1265(3) Å	$\gamma = 90°$
Volume	1867.42(9) Å^3	
Z	2	
Density (calculated)	1.321 Mg/m^3	
Absorption coefficient	0.539 mm^{-1}	
F(000)	776	
Crystal size	0.16 x 0.09 x 0.03 mm^3	
Theta range for data collection	3.00 to 27.54°.	
Index ranges	$-13<=h<=13, -23<=k<=24, -13<=l<=13$	
Reflections collected	19266	
Independent reflections	8163 [R(int) = 0.0579]	
Completeness to theta = 27.54°	98.7%	
Max. and min. transmission	0.9840 and 0.9187	
Refinement method	Full–matrix least–squares on F^2	
Data / restraints / parameters	8163 / 1 / 385	
Goodness–of–fit on F^2	1.076	
Final R indices [I>2sigma(I)]	R1 = 0.0667, wR2 = 0.1217	
R indices (all data)	R1 = 0.0911, wR2 = 0.1343	
Absolute structure parameter	0.00	
Largest diff. peak and hole	0.463 and –0.389 e.Å^{-3}	

Appendix 5.

Identification code	$(S_C,R_{Co},P)^*$–(**555**) [QMULJA388]
Empirical formula	$C_{49}H_{37}Co\ F_3O_2P$
Formula weight	804.7
Temperature	120(2) K
Wavelength	0.71073 Å
Crystal system	Monoclinic
Space group	$P2_1/n$
Unit cell dimensions	a = 12.9334(3) Å $\quad$ α = 90°
	b = 13.7437(4) Å $\quad$ β = 103.477(2)°
	c = 21.5542(6) Å $\quad$ γ = 90°
Volume	3725.82(17) Å^3
Z	4
Density (calculated)	1.435 Mg/m^3
Absorption coefficient	0.561 mm^{-1}
F(000)	1664
Crystal size	0.36 x 0.28 x 0.24 mm^3
Theta range for data collection	2.96 to 27.52°.
Index ranges	$-16<=h<=16,\ -17<=k<=17,\ -27<=l<=27$
Reflections collected	44424
Independent reflections	8518 [R(int) = 0.0705]
Completeness to theta = 27.52°	99.3%
Max. and min. transmission	0.8771 and 0.8235
Refinement method	Full–matrix least–squares on F^2
Data / restraints / parameters	8518 / 0 / 446
Goodness–of–fit on F^2	1.021
Final R indices [I>2sigma(I)]	R1 = 0.0557, wR2 = 0.1231
R indices (all data)	R1 = 0.0899, wR2 = 0.1381
Largest diff. peak and hole	0.736 and -0.530 e.Å^{-3}

Appendix 6.

Identification code	(R_C,S_{Co},M)*–(**566**) [UEAJA432]	
Elemental formula	$C_{48}H_{37}BrCoO_2P$	
Formula weight	815.6	
Crystal system	Monoclinic	
Space group	$P2_1/c$	
Unit cell dimensions	a = 15.8083(2) Å	$\alpha = 90$ °
	b = 12.1120(2) Å	$\beta = 104.196(2)$°
	c = 20.4677(4) Å	$\gamma = 90$ °
Volume	3799.28(11) Å^3	
No. of formula units, Z	4	
Calculated density	1.426 Mg/m^3	
F(000)	1672	
Absorption coefficient	1.586 mm^{-1}	
Temperature	140(1) K	
Wavelength	0.71073 Å	
Crystal colour, shape	deep red prism	
Crystal size	0.58 x 0.40 x 0.37 mm	
Crystal mounting	on a glass fibre, in oil, fixed in cold N_2 stream	
On the diffractometer:	3.2 to 27.5 °	
Theta range for data collection		
Limiting indices	–20<=h<=20, –15<=k<=15, –26<=l<=26	
Completeness to theta = 27.5	98.8%	
Absorption correction	Semi–empirical from equivalents	
Max. and min. transmission	1.031 and 0.980	
Reflections collected (not including absences)	51705	
No. of unique reflections	8637 [R(int) for equivalents = 0.083]	
No. of 'observed' reflections $(I > 2\sigma_I)$	5557	
Structure determined by:	direct methods, in SHELXS	
Refinement:	Full–matrix least–squares on F^2, in SHELXL	
Data / restraints / parameters	8637 / 0 / 478	
Goodness–of–fit on F^2	0.914	
Final R indices ('observed' data)	$R_1 = 0.040$, $wR_2 = 0.083$	
Final R indices (all data)	$R_1 = 0.075$, $wR_2 = 0.089$	
Reflections weighted:	$w = [\sigma^2(Fo^2)+(0.0458P)^2]^{-1}$ where $P=(Fo^2+2Fc^2)/3$	
Largest diff. peak and hole	0.71 and –0.57 e.Å^{-3}	
Location of largest difference peak	near H(123)	

Appendix 7.

Identification code	$(S_C,R_{Co},M)^*-(579)$ [QMULJA361]
Empirical formula	$C_{42}H_{36}CoOP$
Formula weight	646.61
Temperature	120(2) K
Wavelength	0.71073 Å
Crystal system	Monoclinic
Space group	$P\ 2_1/c$

Unit cell dimensions		
	a = 16.305(3) Å	α= 90°
	b = 9.611(2) Å	β= 99.586 (1)°
	c = 20.7989(4) Å	γ= 90°

Volume	3213.8(9) Å^3
Z	4
Density (calculated)	1.336 Mg/m^3
Absorption coefficient	0.617 mm^{-1}
F(000)	1352
Crystal size	0.28 x 0.2 x 0.1 mm^3
Theta range for data collection	3.03 to 27.52°.
Index ranges	–21<=h<=20, –12<=k<=12, –26<=l<=27
Reflections collected	40677
Independent reflections	7330 [R(int) = 0.0496]
Completeness to theta = 27.52°	99.1%
Absorption correction	Muti–scan
Max. and min. transmission	0.938 and 0.861
Refinement method	Full–matrix least–squares on F^2
Data / restraints / parameters	7330 / 0 / 347
Goodness–of–fit on F^2	1.121
Final R indices [I>2sigma(I)]	R1 = 0.0603, wR2 = 0.1385
R indices (all data)	R1 = 0.0776, wR2 = 0.1461
Largest diff. peak and hole	0.955 and –0.461 e.Å^{-3}

Appendix 8.

Identification code	$(S_C, R_{Co}, P)^*$–(567) [UEAJA530]	
Elemental formula	$C_{47}H_{36}ClCoNO_2P \cdot 0.6(H_2O)$	
Formula weight	783.0	
Crystal system	Orthorhombic	
Space group	$Pbc2_1$ (equiv. to no. 29)	
Unit cell dimensions	a = 9.6606(4)	$\alpha = 90$ °
	b = 18.1520(8) Å	$\beta = 90$ °
	c = 20.7926(8) Å	$\gamma = 90$ °
Volume	3646.2(3) $Å^3$	
No. of formula units, Z	4	
Calculated density	1.407 Mg/m^3	
F(000)	1600	
Absorption coefficient	0.630 mm^{-1}	
Temperature	140(1) K	
Wavelength	0.71073 Å	
Crystal colour, shape	deep red plate	
Crystal size	0.37 x 0.37 x 0.13 mm	
Crystal mounting	on a glass fibre, in oil, fixed in cold N_2 stream	
On the diffractometer: Theta range for data collection	3.2 to 24.0 °	
Limiting indices	$-11<=h<=11$, $-20<=k<=20$, $-23<=l<=23$	
Completeness to theta = 24.0	99.7%	
Absorption correction	None applied	
Max. and min. transmission	–	
Reflections collected (not including absences)	36494	
No. of unique reflections	5705 [R(int) for equivalents = 0.116]	
No. of 'observed' reflections $(I > 2\sigma_I)$	4449	
Structure determined by:	direct methods, in SHELXS	
Refinement:	Full–matrix least–squares on F^2, in SHELXL	
Data / restraints / parameters	5705 / 1 / 490	
Goodness–of–fit on F^2	1.099	
Final R indices ('observed' data)	$R_1 = 0.078$, $wR_2 = 0.172$	
Final R indices (all data)	$R_1 = 0.103$, $wR_2 = 0.182$	
Reflections weighted:	$w = [\sigma^2(F_o^2)+(0.1001P)^2]^{-1}$ where $P=(F_o^2+2F_c^2)/3$	
Absolute structure parameter	0.42(4)	
Largest diff. peak and hole	0.70 and -0.48 e.$Å^{-3}$	
Location of largest difference peak	close to Co	

Appendix 9.

Identification code	$(S_{C},_pS)$*–(622) [UEAJA515]	
Elemental formula	$C_{35}H_{32}BrCoNO_2I$	
Formula weight	764.4	
Crystal system	Monoclinic	
Space group	$P2_1/c$	
Unit cell dimensions	a = 14.6341(2) Å	α =90 °
	b = 14.2933(2) Å	β=103.5648(14)°
	c = 15.2857(2) Å	γ = 90 °
Volume	3108.11(7) $Å^3$	
No. of formula units, Z	4	
Calculated density	1.633 Mg/m^3	
F(000)	1520	
Absorption coefficient	2.863 mm^{-1}	
Temperature	140(1) K	
Wavelength	0.71073 Å	
Crystal colour, shape	deep red prism	
Crystal size	0.40 x 0.25 x 0.21 mm	
Crystal mounting	on a glass fibre, in oil, fixed in cold N_2 stream	
On the diffractometer:	3.1 to 27.5 °	
Theta range for data collection		
Limiting indices	–18<=h<=18, –18<=k<=18, –19<=l<=19	
Completeness to theta = 27.5	99.8%	
Absorption correction	Semi–empirical from equivalents	
Max. and min. transmission	1.042 and 0.958	
Reflections collected (not including absences)	43511	
No. of unique reflections	7116 [R(int) for equivalents = 0.053]	
No. of 'observed' reflections (I > $2\sigma_I$)	5171	
Structure determined by:	direct methods, in SHELXS	
Refinement:	Full–matrix least–squares on F^2, in SHELXL	
Data / restraints / parameters	7116 / 0 / 379	
Goodness–of–fit on F^2	0.881	
Final R indices ('observed' data)	R_1 = 0.025, wR_2 = 0.047	
Final R indices (all data)	R_1 = 0.044, wR_2 = 0.049	
Reflections weighted:	$w = [\sigma^2(Fo^2)+(0.0242P)^2]^{-1}$ where $P=(Fo^2+2Fc^2)/3$	
Largest diff. peak and hole	0.52 and –0.50 e.$Å^{-3}$	
Location of largest difference peak	close to H(55)	

Appendix 10.

Identification code	$(S_C,{}_PR)^*–(629)$ [UEAJA547]	
Elemental formula	$C_{40}H_{34}ClCoNO_2F_6P\cdot3(CH_3OH)$	
Formula weight	896.2	
Crystal system	Triclinic	
Space group	P–1	
Unit cell dimensions	a = 11.5087(4) Å	α = 92.422(2) °
	b = 13.0940(3) Å	β = 102.009(3) °
	c = 14.3954(5) Å	γ = 106.070(3) °
Volume	2027.39(11) Å^3	
No. of formula units, Z	2	
Calculated density	1.468 Mg/m^3	
F(000)	928	
Absorption coefficient	0.603 mm^{-1}	
Temperature	140(1) K	
Wavelength	0.71073 Å	
Crystal colour, shape	deep red fragment of block	
Crystal size	*ca* 0.49 x 0.36 x 0.30 mm	
Crystal mounting	on a glass fibre, in oil, fixed in cold N$_2$ stream	
On the diffractometer: Theta range for data collection	3.4 to 27.5 °	
Limiting indices	–14<=h<=14, –16<=k<=17, –18<=l<=18	
Completeness to theta = 27.5	99.4%	
Absorption correction	Semi–empirical from equivalents	
Max. and min. transmission	1.006 and 0.992	
Reflections collected (not including absences)	27112	
No. of unique reflections	9240 [R(int) for equivalents = 0.051]	
No. of 'observed' reflections (I > 2σ$_I$)	6748	
Structure determined by:	direct methods, in SHELXS	
Refinement:	Full–matrix least–squares on F^2, in SHELXL	
Data / restraints / parameters	9240 / 0 / 551	
Goodness–of–fit on F^2	1.018	
Final R indices ('observed' data)	R_1 = 0.040, wR_2 = 0.098	
Final R indices (all data)	R_1 = 0.060, wR_2 = 0.103	
Reflections weighted:	$w = [\sigma^2(Fo^2)+(0.0548P)^2]^{-1}$ where $P=(Fo^2+2Fc^2)/3$	
Largest diff. peak and hole	0.52 and –0.46 e.Å^{-3}	
Location of largest difference peak	near O(7)	