Asymmetric 1,3–Dipolar Cycloaddition Reactions between Methacrylonitrile and Nitrones Catalysed by well–defined M(diphosphane) (M = Rh, Ir) Complexes

Daniel Carmona,*,[a] Fernando Viguri,*,[a] Ainara Asenjo,[a] Pilar Lamata,[a] Fernando J. Lahoz[a] and Pilar García-Orduña[a]

[a] Departamento de Catálisis y Procesos Catalíticos, Instituto de Síntesis Química y Catálisis Homogénea (ISQCH), CSIC - Universidad de Zaragoza, Pedro Cerbuna 12, 50009 Zaragoza, Spain

ABSTRACT

The cationic half–sandwich aqua–complexes $[(\eta^5–C_5Me_5)M(PP^*)(H_2O)][SbF_6]_2$ [M= Rh, Ir; PP*= (R)–Benphos, (R)–Cyphos, (2R,4R)–Norphos] catalyse the 1,3–dipolar cycloaddition reaction (DCR) of nitrones with methacrylonitrile with perfect regioselectivity, low–to–perfect *endo* selectivity and low–to–moderate enantioselectivity. The active species involved in the catalytic process, $[(\eta^5–C_5Me_5)M(PP^*)(methacrylonitrile)][SbF_6]_2$, have been isolated and characterised as mixtures of the (S)– and (R)–at–metal epimers. NMR measurements of these mixtures indicated that the (R_M)–isomers epimerise to the corresponding (S_M) counterparts. The molecular structure of the rhodium complex $(S_{Rh},R_C)–[(\eta^5–C_5Me_5)Rh\{(R)–Benphos\}(methacrylonitrile)][SbF_6]_2$ has been determined by X–ray diffraction methods. Diastereopure $(S_{Rh},R_C)–[(\eta^5–C_5Me_5)Rh(PP^*)(methacrylonitrile)][SbF_6]_2$ compounds catalyse stoichiometrically the above mentioned DCR with up to 90% enantiomeric excess, showing the influence of the metal handeness on the catalytic stereochemical outcome. Catalysts can be recycled up to three times without significant loss of either activity or selectivity.

* Corresponding author. Tel.: +34 976 762027; fax: +34 976 761187
E−mail addresses: dcarmona@unizar.es; fviguri@unizar.es

1. Introduction

Cycloaddition reactions[1] are a fundamental class of processes in synthetic chemistry and among them 1,3–dipolar cycloadditions (DCR) are atom–economic transformations that permit the construction of five–membered heterocycles. Moreover, enantioselective DCR versions allow for the creation of several adjacent stereogenic centres, in a single step with stereochemical control.[2] Over the last years, one of the most studied DCR has been the cycloaddition of nitrones with alkenes (Scheme 1).[3] The resulting isoxazolidines have been applied as valuable synthetic intermediates for the preparation of useful compounds such as alkaloids, β–lactams, amino acids or amino sugars taking advantage of the easy cleavage of the N–O bond of these cyclic compounds under mild reducing conditions.[4]
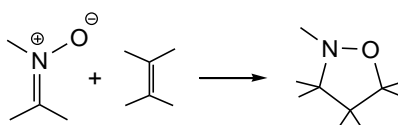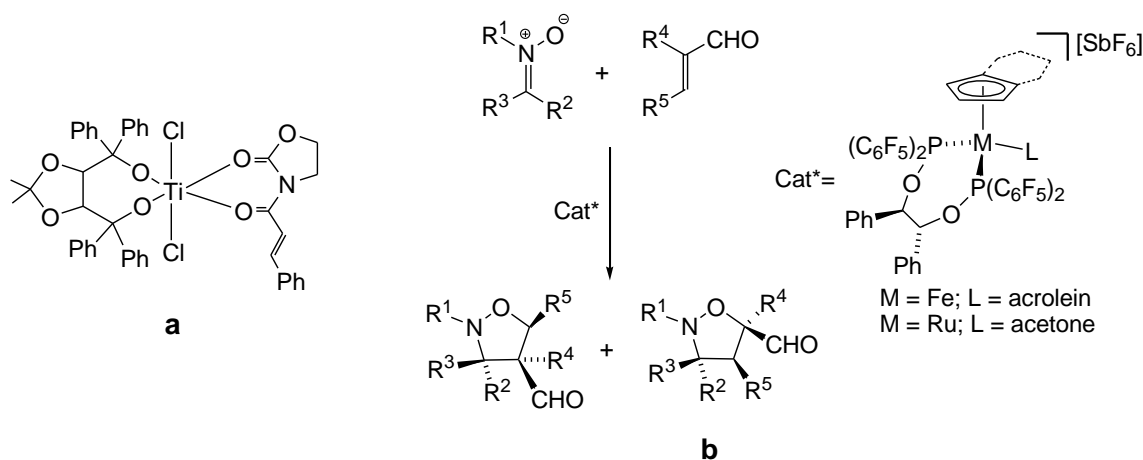
Scheme 1. DCR between nitrones and alkenes.

The greatest challenge for the DCR of nitrones with alkenes is to control the enantioselectivity of the addition. For this purpose, the use of chiral transition–metal Lewis acids as catalysts is one of the most promising approaches. Typically, coordination of a nitrone to the Lewis acid is more feasible than coordination of an alkene.[5] For this reason, asymmetric catalytic reactions in which the dipolarophile is activated by a chiral Lewis acid (normal electron demand) were only successful for substrates such as alkenoyloxazolidinones that enable a bidentate coordination to the Lewis acid and preclude the coordination of the nitrone.[2,3] In fact, the first example of a transition–metal–catalysed asymmetric DCR between alkenes and nitrones exploits this feature using chiral titanium compounds as catalysts.[6] In connection with this work, a

catalytic intermediate featuring the *N*–cinnamoyloxazolidinone coordinated to the metal was isolated and characterised by X–ray crystallography (Scheme 2a).[7]

However, over the last years, a few examples of one–point–binding catalysts for the asymmetric normal electron demand DCR of nitrones with electron–deficient monofunctionalised alkenes have been reported. Thus, in 2002, Kündig *et al.* developed catalytic DCR between nitrones and *α,β*–unsaturated aldehydes in the presence of Binop–F iron and ruthenium complexes as chiral Lewis–acid catalysts (Scheme 2b).[8] Since then, a number of reports dealing with this class of DCR have been published by Kündig, [9] Yamada,[10] Kanemasa,[11] Maruoka,[12] Doyle[13] and ourselves.[5c,14] For this type of catalysts, coordination of the aldehyde is favoured over coordination of the nitrone either via the appropriate choice of the chiral Lewis acid or keeping the nitrone concentration low by adding it slowly to the reaction medium.[8-14]


Scheme 2. Catalytic Intermediate with coordinated *N*–cinnamoyloxazolidinone (**a**) and DCR catalysed by Binop–F complexes (**b**).

On the other hand, the problem of the competitive coordination between nitrones and alkenes can be also circumvented by using alkenes with a good coordinating functionality such as a cyano group. In this context, we have shown that half–sandwich complexes of Rh(III) or Ir(III) containing the chiral fragment $(\eta^5$–$C_5Me_5)M\{(R)$–Prophos\}$ catalyse the DCR of nitrones and *α,β*–unsaturated nitriles.[15]
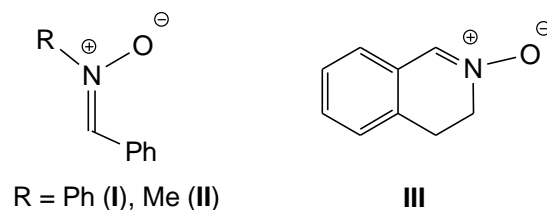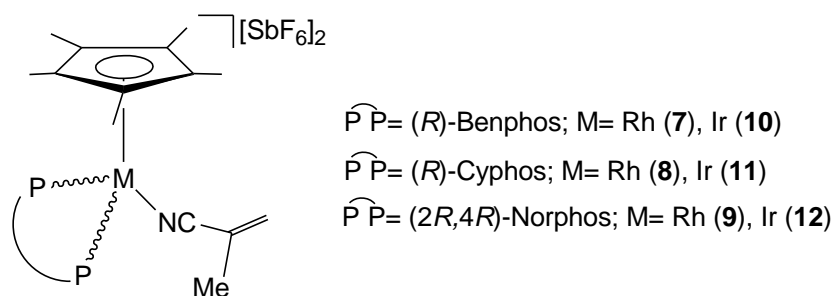
Scheme 3. Nitrones employed in the catalytic experiments.

With all these concerns in mind, herein we report on: i) the catalytic asymmetric DCR of methacrylonitrile with nitrones **I–III** (Scheme 3) using the aqua–complexes (S_M,R_C)–[$(\eta^5$–C$_5$Me$_5)$M(PP*)(H$_2$O)][SbF$_6$]$_2$, [PP*= (R)–Benphos, (R)–Cyphos] and [$(\eta^5$–C$_5$Me$_5)$M{$(2R,4R)$–Norphos}(H$_2$O)][SbF$_6$]$_2$, (M= Rh **1-3**, Ir **4-6**) (Scheme 4)[16]
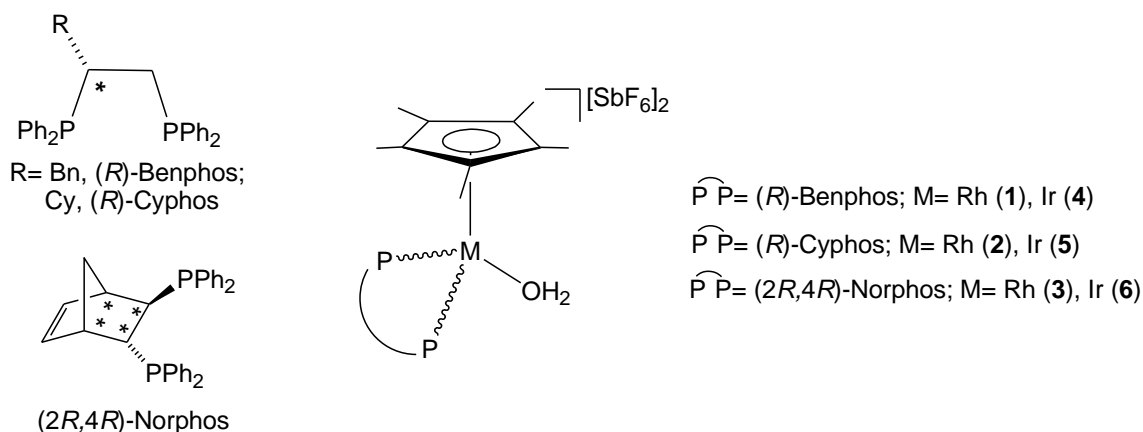
Scheme 4. Aqua–complexes **1-6**.

as catalyst precursors; ii) the preparation and characterization of the corresponding catalytic intermediate complexes [$(\eta^5$–C$_5$Me$_5)$M(PP*)(methacrylonitrile)][SbF$_6$]$_2$ and [$(\eta^5$–C$_5$Me$_5)$M{$(2R,4R)$–Norphos}(methacrylonitrile)][SbF$_6$]$_2$, (M = Rh **7-9**, Ir **10-12**) (Scheme 5), including the determination of the molecular structure by X–ray diffraction of the complex (S_{Rh},R_C)–[$(\eta^5$–C$_5$Me$_5)$Rh{(R)–Benphos} (methacrylonitrile)][SbF$_6$]$_2$ (**7a**) and iii) the use of the (S_M)–epimers of the complexes **7, 8, 11** and **12** as stoichiometric catalysts for the above mentioned 1,3–dipolar cycloaddition reactions.

P̂ P= (R)-Benphos; M= Rh (**7**), Ir (**10**)

P̂ P= (R)-Cyphos; M= Rh (**8**), Ir (**11**)

P̂ P= (2R,4R)-Norphos; M= Rh (**9**), Ir (**12**)

Scheme 5. Methacrylonitrile complexes **7**-**12**.

2. Results and Discussion

2.1. Catalytic Studies

The aqua–complexes (S_M,R_C)–$[(\eta^5$–$C_5Me_5)M(PP^*)(H_2O)][SbF_6]_2$, [PP* = (R)–Benphos, (R)–Cyphos] and $[(\eta^5$–$C_5Me_5)M\{(2R,4R)$–Norphos$\}(H_2O)][SbF_6]_2$, (M = Rh **1**-**3**, Ir **4-6**) were tested as catalyst precursors for the DCR reaction between methacrylonitrile and linear (N–benzylidenphenylamine N–oxide (**I**), N–benzylidenmethylamine N–oxide (**II**)) and cyclic (2,3,4,5–dihydroisoquinoline N–oxide (**III**)) nitrones.

Table 1 lists a selection of the results together with the reaction conditions employed. The collected results are the average of at least two comparable reaction runs. Conversion, regio– and diastereo–selectivity were determined by NMR spectroscopy and enantioselectivity was determined by HPLC. With linear nitrones **I** and **II**, rates were low (16-46% conversion, 90 hours, entries 1-6). Reactions are faster with cyclic nitrone **III** (75-85% conversion, 16 hours, entries 7-9). Iridium catalysts are less active (and selective) than the rhodium–based homologues (entries 10-12).

Perfect 3,5 regioselectitvity was obtained in all cases and, as expected for Lewis acid–catalyzed DCR of nitrones with one–point binding alkenes, an *endo* preference was shown.[17] Linear nitrone **I** gave high diastereoselectivity in 3,5–*endo* with poor enantioselectivity (entries 1-3) and nitrone **II** afforded both 3,5 cycloadducts with poor diastereoselectivity and moderated enantioselectivity (entries 4-6). With nitrone **III**,

5

perfect diastereoselectiviy in the 3,5–*endo* cycloadduct was achieved with e. e. values

around 65% (entries 7-9).

Table 1
Enantioselective DCR of methacrylonitrile with nitrones **I–III** catalysed by **1–6**[a].

R = Ph (**I**), Me (**II**)

III

(3S*,5S*)-*endo* + (3R*,5S*)-*exo*

(3S*,5R*)-*endo*
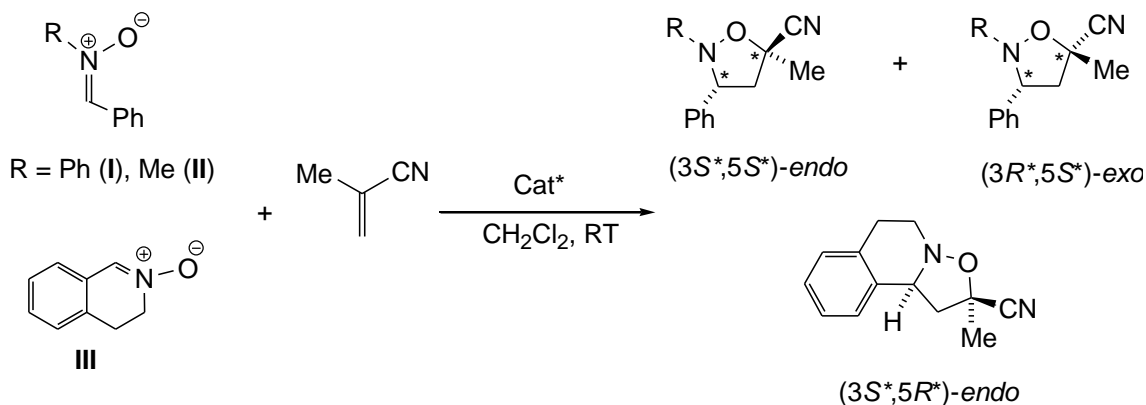
Entry	Catalyst	Nitrone	t (h)	Conv. (%)[b,c]	Isomer ratio (%) 3,5-*endo*/3,5-*exo*[c]	e. e. (%)[d] *endo*/*exo*
1	**1** (Rh/Benphos)	**I**	90	46	86/14	rac/6
2	**2** (Rh/Cyphos)	**I**	90	28	90/10	rac/7
3	**3** (Rh/Norphos)	**I**	90	30	85/15	rac/5
4	**1** (Rh/Benphos)	**II**	90	19	50/50	60/55
5	**2** (Rh/Cyphos)	**II**	90	18	52/48	65/69
6	**3** (Rh/Norphos)	**II**	90	16	56/44	63/67
7	**1** (Rh/Benphos)	**III**	16	83	100/-	61/-
8	**2** (Rh/Cyphos)	**III**	16	85	100/-	65/-
9	**3** (Rh/Norphos)	**III**	16	75	100/-	68/-
10	**4** (Ir/Benphos)	**III**	16	44	100/-	rac/-
11	**5** (Ir/Cyphos)	**III**	16	35	100/-	rac/-
12	**6** (Ir/Norphos)	**III**	16	37	100/-	6/-

[a] Reaction conditions: catalyst 0.03 mmol (10 mol %), methacrylonitrile 2.1 mmol, nitrone 0.30 mmol, in 4 mL of CH_2Cl_2, at RT.
[b] Based on nitrone.
[c] Determined by ^1H NMR.
[d] Determined by HPLC.

To get a deeper insight into the catalytic reaction we next investigated the

intermediate complexes involved in the process.

2.2. Preparation of the complexes [(η^5–C$_5$Me$_5$)M(PP)(methacrylonitrile)][SbF$_6$]$_2$ (**7-**

12)*

The title complexes were prepared in nearly quantitative yield by addition of methacrylonitrile to the corresponding aqua–complexes **1-6** (Eq. 1). The reaction afforded mixtures of the two possible epimers at the metal, namely S_M (which we will label with an **a**) and R_M (labelled **b**). The diastereomeric ratio of formation is quoted in Eq. 1. and, as it can be seen, low diastereomeric excesses were achieved ($\leq$ 36%). The configuration at the metal centre was assigned by NOE measurements (see below).

$$[(\eta^5\text{-}C_5Me_5)M(PP^*)(H_2O)][SbF_6]_2 \quad + \quad \overset{CN}{\underset{Me}{=\!\!\!<}} \quad \xrightarrow{-H_2O}$$
$$\mathbf{1\text{-}6}$$

$$\longrightarrow \quad [(\eta^5\text{-}C_5Me_5)M(PP^*)(\text{methacrylonitrile})][SbF_6]_2 \qquad \text{(Eq. 1)}$$
$$\mathbf{7\text{-}12}$$
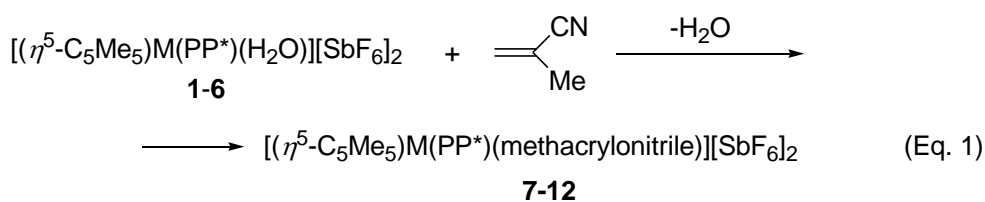
PP* = Benphos; M = Rh **7a/7b** : 47/53, M = Ir **10a/10b** : 68/32
Cyphos;   M = Rh **8a/8b** : 58/42, M = Ir **11a/11b** : 67/33
Norphos; M = Rh **9a/9b** : 56/44, M = Ir **12a/12b** : 53/47

The new complexes were characterised by analytical and spectroscopic means including two–dimensional homo– and hetero–nuclear NMR correlations. In addition, the crystal structure of the rhodium methacrylonitrile complex **7a** has been determined by X–ray diffractometric methods.

The ^{1}H NMR spectra, apart from the typical peaks of the coordinated diphosphane and C_5Me_5 ligands, show the presence of coordinated methacrylonitrile. A singlet in the 1.5-1.7 ppm region is assigned to the methyl group and two resonances in the 5.0-6.2 ppm region, that correlate with two ^{13}C NMR peaks in the 114-115 (NC−C=C) and 140-141 (NC−C=C) ppm intervals, are attributed to the olefinic protons. The CN carbon resonates at around 119 ppm, for the Benphos and Cyphos complexes and in the 126-131 ppm region for the Norphos complexes. In addition, a sharp IR band at around 2255 cm^{-1}, shifted about 26 cm^{-1} towards higher frequency with respect to free methacrylonitrile, is attributed to the C≡N functionality.

The ^{31}P NMR spectra consist of two doublets of doublets (Rh–P coupling constants of about 120-130 Hz and P–P couplings of about 40 Hz) for the rhodium complexes and two doublets for the iridium ones, with a P–P coupling of about 13 Hz.

A NOE correlation between the H_{11} (complexes **7**, **8**, **10** and **11**) or H_2 proton (complexes **9** and **12**) (see Scheme **7** for labelling) and the methyl protons of the coordinated methacrylonitrile strongly indicates an *S* configuration at the metal (isomers labelled **a**).

Mixtures of the *R*– and *S*–at–metal isomers epimerise to the *S*–at–metal epimer at different rate depending on both, the metal and the phospane. Thus, starting from slightly diastereoenriched samples of the Benphos and Cyphos rhodium compounds **7** and **8**, diastereopure **7a** and **8a** are obtained after 1 hour of treatment at RT, in acetone. However, to obtain in diastereopure form the iridium analogues **10a** and **11a**, it is necessary to reflux the starting epimeric mixtures in acetone over 6 hours. Finally, mixtures of the Norphos isomers **9a/9b** (12% d. e.) and **12a/12b** (6% d. e.) evolve up to about 40% d. e. in favour of the (*S*)−epimer, after refluxing in acetone for 6 hours.
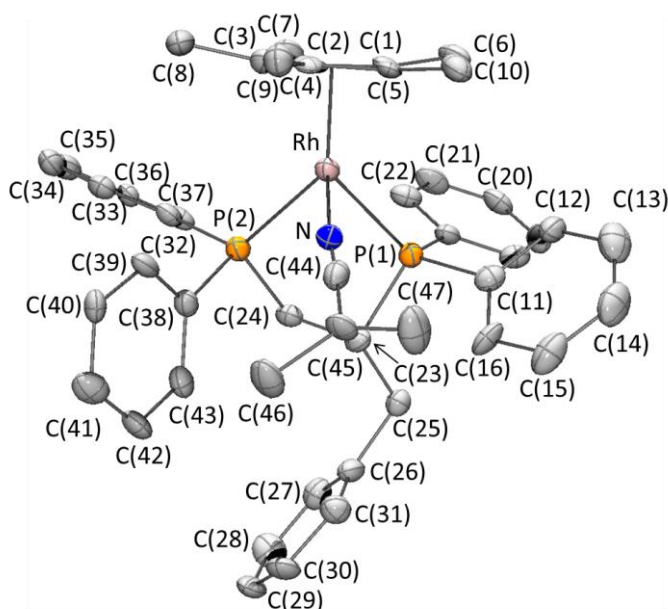
2.3. Molecular structure of compound *7a*

Single crystals suitable for X–ray diffraction analysis were obtained by slow diffusion of *n*–hexane into dichloromethane solutions of complex **7a**. A molecular representation of the complex is depicted in Figure 1 and relevant structural parameters are summarized in Table 2. The metal atom exhibits a formal pseudo–tetrahedral environment being coordinated to an η^5–C_5Me_5 group, to the two phosphorus atoms of the (*R*)–Benphos ligand and to the nitrogen atom of the nitrile. The absolute configuration at the metal is *S*, in accordance with the ligand priority sequence η^5–C_5Me_5 > P(1) >P(2) > N.[18] The M−P(1)−C(23)−C(24)−P(2) metallacycle exhibits a λ

conformation with highly puckered [3]E envelope conformation (Cremer and Pople parameters $Q = 0.570(9)$Å, $\phi = 75.3(5)°$).[19]

The bond lengths and angles in the metal coordination sphere match with those reported in closely related complexes. For instance, Rh−P and Rh−Ct (C_5Me_5 centroid) bond lengths do not significantly differ from the values found in $[(\eta^5–C_5Me_5)Rh\{(R)-$Benphos$\}$(methacrolein)$]^{+2}$ complex (Rh−P(1) : 2.331(2), Rh−P(2) : 2.360(2) and Rh−Ct : 1.854(9) Å)[16] while Rh−N bond length nicely agrees with that reported in $[(\eta^5–C_5Me_5)Rh\{(R)-$Prophos$\}$(methacrylonitrile)$]^{+2}$ complex (Rh−N : 2.067(7)Å).[15a]


Figure 1. Molecular structure of the cation of **7a**.

Table 2. Selected bond distances (Å) and angles (°) for the complex **7a**

Rh-P(1)	2.334(3)	P(1)-Rh-N	86.1(3)
Rh-P(2)	2.358(3)	P(1)-Rh- Ct[a]	130.8(2)
Rh-N	2.056(9)	P(2)-Rh-N	90.3(2)
Rh-Ct[a]	1.8520(2)	P(2)-Rh- Ct[a]	131.2(2)
N-C(44)	1.156(13)	N-Rh- Ct[a]	120.8(3)
C(44)-C(45)	1.447(15)	Rh-N-C(44)	174.8(9)
C(45)-C(46)	1.504(14)	N-C(44)-C(45)	176.7(12)
C(45)-C(47)	1.341(15)	C(44)-C(45)-C(46)	115.7(10)
P(1)-Rh-P(2)	83.49(10)	C(44)-C(45)-C(47)	116.7(10)

[a]Ct represents the centroid of the η^5-C_5Me_5 ring.

The unsaturated nitrile fragment N−C(44)−C(45)−C(47) is essentially planar. The bond distances along this conjugated system, [N−C(44) 1.156(13), C(44)−C(45) 1.447(15), C(45)−C(47) 1.341(15) Å], evidence the partial delocalisation of the π–electron density and justify the decreasing of the ν(CN) frequency measured in the IR of these complexes.[20]
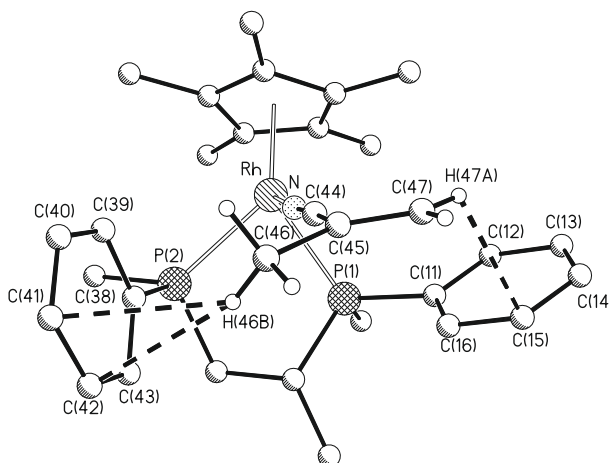
Figure 2. CH/π interactions in complex **7a**.

Table 3
Selected geometrical parameters (Å,°) concerning CH/π interactions for complex **7a.**

	H···G [a]	H···Ph [b] (plane)	γ angle [c]	C-H···C [d]	C-H···C(Ph) [e]
C(47)-H(47A)···C(11)/C(16)	3.45	2.74	37.5	C(15): 2.85	3.17- 4.43
C(46)-H(46B)···C(38)/C(43)	2.88	2.78	15.5	C(41): 2.89 C(42): 2.89	3.16 - 3.54

[a] H···G: separation between hydrogen atom and the centroid of the phenyl ring.
[b] H···Ph (plane) represents the distance from the H atom to the mean plane of the phenyl ring of the reported C-H···π interaction.
[c] γ angle: angle between the G-H vector and the normal to the phenyl ring.
[d] CH···C: distance between H atom and the phenyl carbon atom under the assumed criterium (3.05Å).
[e] CH···C(Ph): range of distances between H atom and the rest of the carbon atoms of the π system.

Due to the linearity of the Rh−N−C(44)−C(45) moiety, [Rh−N−C(44) = 174.8(9)°, N−C(44)−C(45) = 176.7(12)°] the relative disposition of the methacrylonitrile ligand within the metal coordination sphere could be characterised by the Ct−Rh···C(45)−C(47) torsion angle that relates the nitrile and C$_5$Me$_5$ planes. While angles close to 90° indicate a parallel arrangement for both planes, values close to 0° (or 180°) point to a relative perpendicular disposition between them. The measured value,

–68.4(9)º, identifies an intermediate disposition. The absolute value of this angle is comparable to that reported (74.5º) for the homologue (*R*)–Prophos metacrylonitrile rhodium compound.[15a] This arrangement favours the establishment of CH/π interactions[21] between an olefinic proton of the methacrylonitrile [H(47A)] and the C(15)−C(16) bond of the *pro–S* phenyl ring of the P(1)PPh$_2$ group, as well as between a hydrogen of the CH$_3$ group of the methacrylonitrile [H(46B)] and the C(41)–C(42) double bond of the *pro–R* phenyl ring of the P(2)Ph$_2$ fragment (Figure 2). These interactions are characterised by short H⋯phenyl plane ring separations and H⋯C interatomic distances, clearly shorter than the sum of the van der Waals radii (Table 3).

In the encountered conformation, the *Si* face of the coordinated nitrile becomes shielded by the *pro–S* phenyl ring of the P(1)PPh$_2$ group involved in the CH/π interactions and, therefore, the attack of the nitrone would preferentially occur through the *Re* face of this substrate.

2.4. Stoichiometric Reactions

The preparation of complexes **7-12** according to Eq. 1, clearly establishes that both epimers at metal are present during the catalytic reactions above reported. Assuming that both are active in catalysis, enantioselectivity could be eroded if they induce divergently. Taking advantage of the observed epimerization of the **b** isomers to the corresponding **a** epimers (see above), we prepared pure samples of the S_M diastereomers for the Benphos and Cyphos containing compounds **7**, **8**, **10** and **11**. Trying to improve the enantioselectivity, we carried out stoichiometric reactions between the enantiopure S_M isomers **7a**, **8a**, **10a** and **11a** and nitrones **I–III** (Equation 2). We also performed the stoichiometric CDR reactions using as catalyst mixtures of the Norphos compounds **9a,b** and **12a,b** enriched in the **a** epimer (40% d. e. in both cases). Table 4 collects a selection of the results obtained along with the reaction conditions.

(Eq. 2)
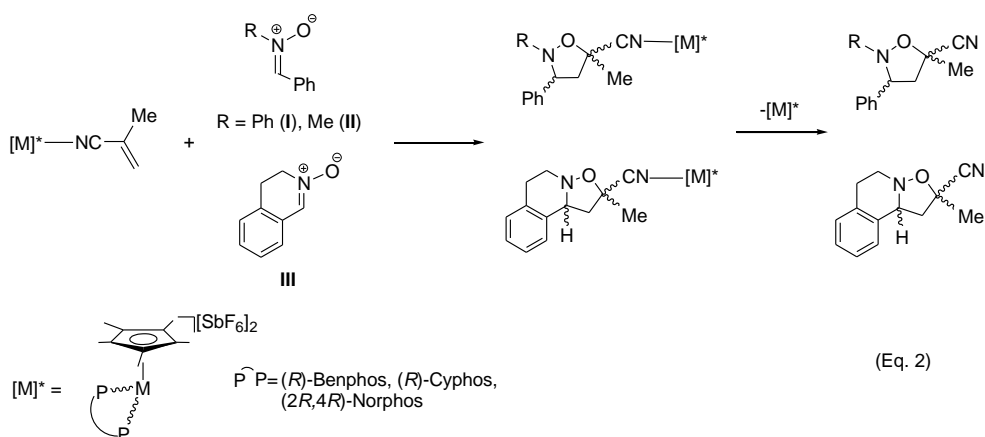
Table 4
Stoichiometric DCR of methacrylonitrile catalysed by **7-12**[a].

Entry	Catalyst	Nitrone	Isomer ratio 3,5-*endo*/3,5-*exo*(%)[b]	e. e. (%)[c] *endo/exo*
1	**7** (Rh/Benphos)	**I**	77/23	26/30
2	**8** (Rh/Cyphos)	**I**	77/23	40/47
3	**9** (Rh/Norphos)	**I**	82/18	29/26
4	**7** (Rh/Benphos)	**II**	39/61	77/80
5	**8** (Rh)/Cyphos)	**II**	42/58	84/82
6	**9** (Rh/Norphos)	**II**	44/56	72/70
7	**7** (Rh/Benphos)	**III**	100/-	72/-
8	**8** (Rh/Cyphos)	**III**	100/-	90/-
9	**9** (Rh/Norphos)	**III**	100/-	86/-
10	**10** (Ir/Benphos)	**III**	100/-	51/-
11	**11** (Ir/Cyphos)	**III**	100/-	56/-
12	**12** (Ir/Norphos)	**III**	100/-	22/-

[a] Reaction conditions: catalyst, a 7.5×10^{-2} M solution in 4 mL of CH_2Cl_2; nitrone, 5 equiv. in 1 mL of CH_2Cl_2; 3h at RT.
[b] Determined by ^{1}H NMR.
[c] Determined by HPLC.

A slight decrease in the diastereoselectivity was observed for the reaction between the rhodium complexes and the linear nitrones **I** and **II** (compare entries 1-6 in Table 4 with the corresponding entries in Table 1). The perfect selectivity, in favour of the 3,5–*endo* cycloadduct for the cyclic nitrone **III**, was not affected (entries 7-12).

In these stoichiometric reactions, a notable and generalised increase in the e. e. values was observed in relation to those obtained in sub–stoichiometric runs. Thus, for

example, whereas employing a mixture of the two Rh/Cyphos epimers **8a**/**8b** as catalyst gives no significant e. e. for the reaction between methacrylonitrile and nitrone **I** (entry 2, Table 1), using enantiopure **8a** gives, for the same reaction, 40 % and 47 % e. e. in the 3,5–*endo* and in the 3,5–*exo* cycloadducts, respectively (entry 2, Table 4). Similarly, 90 % e. e. in the 3,5–*endo* adduct was obtained in the reaction between methacrylonitrile and nitrone **III** when stereopure complex **8a** was employed as catalyst (entry 8, Table 4), in contrast to the 65 % e. e. obtained when **8a**/**8b** mixtures were used (entry 8, Table 1). The employ of diastereoenriched mixtures of the Norphos complexes **9** and **12** in a stoichiometric manner also improves the e. e.; in particular, 86% e. e. was achieved for nitrone **III** (entry 9, Tables 1 and 4). These results strongly indicate that changing the metal configuration reverses the induction sign and renders antipode adducts *i. e.* metal configuration governs the stereoselectivity.

2.5. Recycling experiments

Finally, trying to increase the ratio adduct/catalyst without loss of e. e., we carried out recycling experiments using the reaction between nitrone **III** and methacrylonitrile catalysed by complex **8** as a model. Scheme 6 shows the procedure developed to this end. In the first step, 5 equivalents of nitrone were added to diastereopure (S_M,R_C)–**8**. After the required reaction time, excess of nitrone was extracted in Et_2O/CH_2Cl_2 to avoid the simultaneous presence of nitrone, alkene, and catalyst in the reaction medium. The adduct was dissociated from the rhodium complex by adding 20 equivalents of alkene with concomitant formation of a mixture of the (S_M,R_C)–**8** and (R_M,R_C)–**8** epimers. The adduct and the excess of nitrile were extracted in Et_2O/CH_2Cl_2, and from the extract, the adduct was isolated and characterised. The (S_M,R_C)–**8** and (R_M,R_C)–**8** mixture was allowed to epimerise to (S_M, R_C)–**8**, which, after addition of new nitrone, restarts a further catalytic run. Following this procedure, **8a** renders the 3,5-*endo*

cycloadduct in 88% yield and 80% e. e. and in 90% yield and 78% e. e. in the second and third run, respectively.
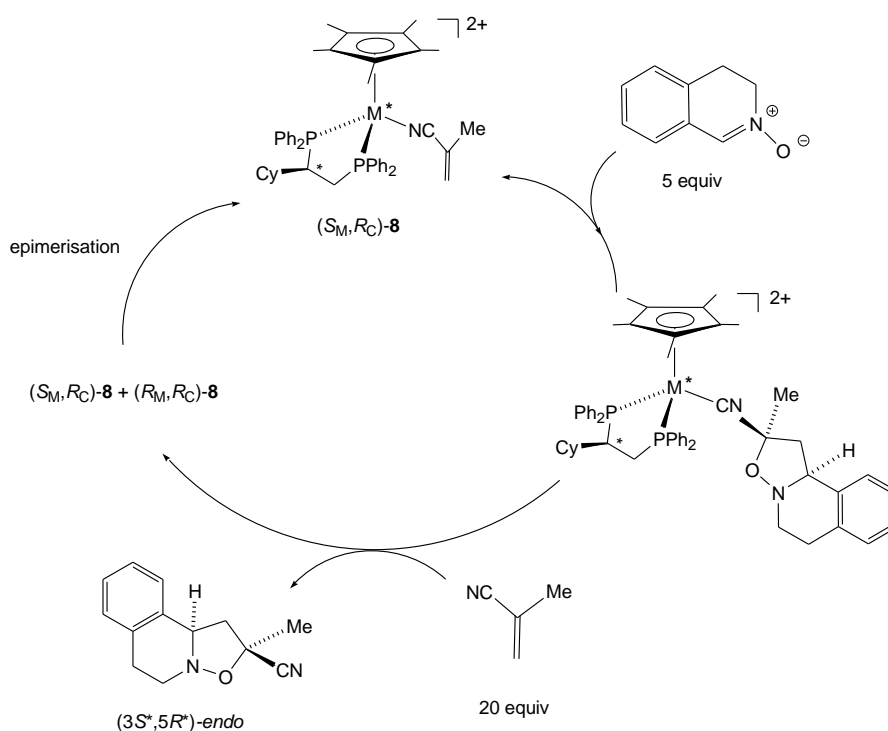
Scheme 6. Recycling experiments.

3. Conclusions

Catalysts based on the chiral Lewis acid fragment $(\eta^5-C_5Me_5)M(PP^*)$ (M= Rh, Ir; PP*= enantiopure chiral diphosphane) generate efficient systems for the 1,3–dipolar cycloaddition reaction between methacrylonitrile and nitrones. The employ of alkenes containing a good coordinating functionality allows the complete characterization of the substrate–catalyst intermediates formed during catalysis, as well as the optimization of the catalytic system performance. The e. e. achieved in stoichiometric reactions compared to those in sub–stoichiometric catalytic runs, strongly indicate that enantioselectivity is controlled by the metal centre. Finally, catalysts can be recycled up to three times without significant loss of activity and selectivity.

4. Experimental Section

4.1. Material and instrumentation

All solvents were dried over appropriate drying agents, distilled under argon and degassed prior to use. All preparations have been carried out under argon. Infrared spectra were obtained as KBr pellets with a Perkin-Elmer Spectrum One FT IR spectrophotometer. Carbon, hydrogen and nitrogen analyses were performed using a Perkin–Elmer 240C microanalyzer. ^{1}H, ^{13}C and ^{31}P NMR spectra were recorded on Bruker AV–500 (500.13 MHz), AV–400 (400.16 MHz) or ARX–300 (300.10 MHz) spectrometers. Chemical shifts are expressed in ppm up field from $SiMe_4$ or 85% H_3PO_4 (^{31}P). NOESY and ^{13}C, ^{31}P and ^{1}H correlation spectra were obtained using standard procedures. Optical rotation was recorded on a Perkin–Elmer 241 polarimeter (10 cm cell, 589 nm). Analytical high performance liquid chromatography (HPLC) was performed on an Alliance Waters (Waters 2996, PDA detector) instrument using a chiral column Daicel Chiracel OD–H (0.46 cm × 25 cm) with OD–H guard (0.46 cm × 25 cm) or Chiralpak AD–H (0.46 cm × 25 cm) columns.

Complexes **1-6** were prepared using literature procedures.[16]

4.2. Catalytic Procedure

At –25 ºC, the corresponding aqua–complex [(η^5–C_5Me_5)M(PP*)(H_2O)][SbF_6]$_2$ (**1-6**) (0.03 mmol, 10 mol %), NC(Me)C=CH_2 (2.10 mmol) and CH_2Cl_2 (3 mL) were stirred for 30 min. To the resulting solution, nitrone (0.30 mmol) in CH_2Cl_2 (1 mL) was added. After stirring at the indicated temperature for the appropriate reaction time, 20 mL of *n*–hexane were added. After filtration over Celite, the solution was evaporated to dryness. Conversion and regioselectivity were determined in $CDCl_3$ solutions of the crude mixture by ^{1}H NMR. The residue was purified by chromatography (SiO_2) to provide the corresponding isoxazolidine. The enantiomeric excess was determined by HPLC (for details see Supplementary Material).

4.3. Preparation of [(η^5–C_5Me_5)M(PP)(NC(Me)C=CH_2)][SbF_6]$_2$ (**7-12**)*

At −25 °C under argon, to a solution of the corresponding complex $[(\eta^5-$ $C_5Me_5)M(PP^*)(H_2O)][SbF_6]_2$ (0.13 mmol) in CH_2Cl_2 (5 mL), $NC(Me)C=CH_2$ (0.26 mmol) was added. The resulting yellow solution was stirred for 5 min and then the solvent was vacuum–evaporated to dryness. The diastereomeric composition of the residue was determined by NMR. The residue was re–dissolved in a minimum amount of CH_2Cl_2 (about 1mL) and the addition of 20 mL of dry *n*–hexane afforded a yellow solid that was filtered off, washed with *n*–hexane and vacuum–dried.
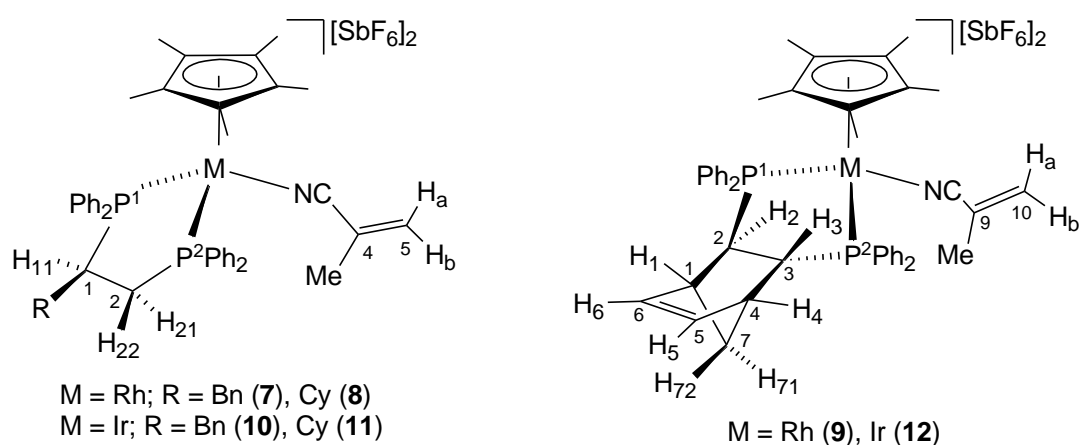
Scheme 7. Labelling of the methacrylonitrile complexes **7-12**, for NMR assignments.

4.3.1. Compound 7, R= Bn

Yield: 87%. IR (cm^{-1}): ν(CN) 2255 (m), ν(SbF$_6$) 651 (s). Anal. Calcd for $C_{47}H_{50}F_{12}RhNP_2Sb_2$: C, 44.6; H, 4.0; N, 1.1. Found: C, 44.1; H, 3.7; N, 1.1.

7a, (S_{Rh})–Isomer, 47%: $[\alpha]_D^{25}= 11.0$ (c = 0.60 in CH_2Cl_2). ^{1}H–RMN (500.10 MHz, CD_2Cl_2, 25 °C): δ = 8.00–7.15 (m, 25H, Ph), 5.96 (s, 1H, H$_b$), 5.16 (s, 1H, H$_a$), 3.29 (d, *J* = 13.0 Hz, 1H, CH*H*Ph), 3.10 (dt, *J* = 53.5, 13.6 Hz, 1H, H$_{22}$), 2.80 (m, 1H, H$_{11}$), 2.39 (m, 1H, H$_{21}$), 1.96 (t, *J* = 13.0 Hz, 1H, C*H*HPh), 1.52 (t, *J* = 2.2 Hz, 15H, C_5Me_5), 1.49 ppm (s, 3H, Me). ^{13}C–RMN (125.77 MHz, CD_2Cl_2, 25 °C): δ = 140.29 (C^5), 137.72–123.74 (25C, Ph), 119.96 (CN), 114.69 (C^4), 107.74 (d, *J* = 4.8 Hz, C_5Me_5), 38.74 (dd, *J* = 29.0, 10.3 Hz, C^1), 36.01 (d, *J* = 16.4, 4.1 Hz, *C*H$_2$Ph), 29.03 (dd, *J* = 29.0, 10.3 Hz, C^2), 19.02 (Me), 9.20 ppm (C_5Me_5). ^{31}P–RMN (202.46 MHz, CD_2Cl_2, 25 °C): δ = 68.81

(dd, $J(\text{Rh},\text{P}^1)$ = 123.2 Hz, $J(\text{P}^1,\text{P}^2)$ = 38.1 Hz, P^1), 41.75 ppm (dd, $J(\text{Rh},\text{P}^2)$ = 125.8 Hz, P^2).

7b, (R_{Rh})–Isomer, 53%: ^{1}H–RMN (300.10 MHz, CD_2Cl_2, –25 ºC): δ = 5.81 (d, J = 1.5 Hz, 1H, H_b), 5.16 (s, 1H, H_a), 3.02 (m, 1H, CH*H*Ph), 1.51 (t, J = 2.2 Hz, 15H, C_5Me_5), 1.49 ppm (s, 3H, Me). ^{31}P–RMN (121.48 MHz, CD_2Cl_2, –25 ºC): δ = 67.00 (dd, $J(\text{Rh},\text{P}^1)$ = 126.3 Hz, $J(\text{P}^1,\text{P}^2)$ = 33.6 Hz, P^1), 57.60 ppm (dd, $J(\text{Rh},\text{P}^2)$ = 123.4 Hz, P^2).

4.3.2. Compound 8, R= Cy

Yield: 91%. IR (cm^{-1}): ν(CN) 2257 (m), ν(SbF$_6$) 653 (s). Anal. Calcd for $C_{46}H_{54}F_{12}RhNP_2Sb_2$: C, 43.9; H, 4.3; N, 1.1. Found: C, 43.6; H, 4.0; N, 1.1.

8a, (S_{Rh})–Isomer, 58%: $[\alpha]_D^{25}$= 5.8 (c = 1.02 in CH_2Cl_2). ^{1}H–RMN (400.16 MHz, CD_2Cl_2, 25 ºC): δ = 7.96–7.33 (m, 20H, Ph), 5.90 (bs, 1H, H_b), 5.17 (bs, 1H, H_a), 3.38 (dt, J = 54.3, 12.4 Hz, 1H, H_{22}), 2.49 (m, 1H, H_{21}), 2.44 (m, 1H, H_{11}), 1.60–0.70 (m, 11H, Cy), 1.50 (t, J = 3.5 Hz, 3H, Me), 1.46 ppm (t, J = 3.5 Hz, 15H, C_5Me_5). ^{13}C–RMN (100.61 MHz, CD_2Cl_2, 25 ºC): δ = 140.02 (C^5), 135.02–121.32 (24C, Ph), 120.74 (CN), 114.72 (C^4), 107.60 (d, J = 4.8Hz, C_5Me_5), 42.38-25.51 (6C, Cy), 38.18 (dd, $J(\text{P},\text{C})$ = 14.1, 5.3 Hz, C^1), 26.56 (q, J = 14.9 Hz, C^2), 18.98 (Me), 9.11 ppm (C_5Me_5). ^{31}P–RMN (161.96 MHz, CD_2Cl_2, 25 ºC): δ = 73.73 (dd, $J(\text{Rh},\text{P}^1)$ = 121.8 Hz, $J(\text{P}^1,\text{P}^2)$ = 37.8 Hz, P^1), 44.91 ppm (dd, $J(\text{Rh},\text{P}^2)$ = 126.4 Hz, P^2).

8b, (R_{Rh})–Isomer, 42%: ^{1}H–RMN (400.16 MHz, CD_2Cl_2, -25 ºC): δ = 5.85 (d, J = 1.6 Hz, 1H, H_b), 5.25 (bs, 1H, H_a), 3.28 (m, 1H, H_{22}), 2.85 (m, 1H, H_{21}), 2.77 (m, 1H, H_{11}), 1.46 (s, 3H, Me), 1.41 ppm (t, J = 3.3 Hz, 15H, C_5Me_5). ^{31}P–RMN (161.96 MHz, CD_2Cl_2, -25 ºC): δ = 59.56 (dd, $J(\text{Rh},\text{P}^1)$ = 123.8 Hz, $J(\text{P}^1,\text{P}^2)$ = 37.7 Hz, P^1), 53.58 ppm (dd, $J(\text{Rh},\text{P}^2)$ = 121.9 Hz, P^2).

4.3.3. Compound 9

Yield: 91%. IR (cm^{-1}): ν(CN) 2253 (m), ν(SbF$_6$) 652 (s). Anal. Calcd for C$_{45}$H$_{48}$F$_{12}$RhNP$_2$Sb$_2$: C, 43.6; H, 3.9; N, 1.1. Found: C, 43.8; H, 4.0; N, 1.1.

9a, (S_{Rh})–Isomer, 56%: ^{1}H–RMN (300.10 MHz, CD$_2$Cl$_2$, 25 °C): δ = 7.96–7.17 (m, 20H, Ph), 6.16 (dd, J = 5.4, 3.0 Hz, 1H, H$_5$), 6.01 (s, 1H, H$_b$), 5.39 (s, 1H, H$_a$), 4.92 (dd, J = 5.4, 3.0 Hz, 1H, H$_6$), 3.44 (s, 1H, H$_1$), 3.21 (bs, 1H, H$_2$), 3.10 (s, 1H, H$_4$), 3.08 (m, 1H, H$_3$), 2.12 (m, 2H, H$_{71}$, H$_{72}$), 1.64 (s, 3H, Me), 1.56 ppm (t, J = 3.7 Hz, 15H, C$_5$Me$_5$). ^{13}C–RMN (75.50 MHz, CD$_2$Cl$_2$, 25 °C): δ = 140.94 (d, J = 7.3 Hz, C^5), 140.30 (C^{10}), 135.33–123.13 (24C, Ph), 130.75 (C^6), 127.03 (CN), 115.09 (C^9), 106.39 (d, J = 5.5 Hz, C_5Me$_5$), 52.81 (m, C^7), 51.00 (dd, J = 26.7, 17.7 Hz, C^3), 45.17 (dd, J = 35.6, 17.5 Hz, C^2), 43.96 (dd, J = 9.0, 7.5 Hz, C^1), 41.88 (dd, J = 13.2, 7.8 Hz, C^4), 18.99 (Me), 9.39 ppm (C$_5$$Me_5$). ^{31}P–RMN (121.48 MHz, CD$_2$Cl$_2$, 25 °C): δ = 39.86 (dd, J(Rh,P^1) = 124.3 Hz, J(P^1,P^2) = 41.2 Hz, P^1), 30.60 ppm (dd, J(Rh,P^2) = 131.1 Hz, P^2).

9b, (R_{Rh})–Isomer, 44%: ^{1}H–RMN (300.10 MHz, CD$_2$Cl$_2$, 25 °C): δ = 6.74 (dd, J = 5.4, 3.1 Hz, 1H, H$_5$), 6.11 (s, 1H, H$_b$), 6.09 (dd, J = 5.4, 3.1 Hz, 1H, H$_6$), 5.56 (s, 1H, H$_a$), 3.46 (bs, 1H, H$_2$), 3.27 (s, 1H, H$_1$), 2.90 (s, 1H, H$_4$), 2.45 (t, J = 13.8 Hz, 1H, H$_3$), 1.78 (m, 1H, H$_{72}$), 1.73 (s, 3H, Me), 1.58 (s, 15H, C$_5$Me$_5$), 0.41 ppm (d, J = 9.2 Hz, 1H, H$_{71}$). ^{13}C–RMN (75.50 MHz, CD$_2$Cl$_2$, 25 °C): δ = 142.15 (d, J = 8.0 Hz, C^5), 140.54 (C^{10}), 133.40 (C^6), 127.22 (CN), 115.16 (C^9), 106.67 (d, J = 5.5 Hz, C_5Me$_5$), 52.07 (d, J = 10.9 Hz, C^7), 48.58 (dd, J = 33.9, 19.2 Hz, C^3), 47.21 (dd, J = 27.9, 15.8 Hz, C^2), 43.65 (C^1), 41.30 (dd, J = 11.8, 6.6 Hz, C^4), 19.02 (Me), 9.40 ppm (C$_5$$Me_5$). ^{31}P–RMN (121.48 MHz, CD$_2$Cl$_2$, 25 °C): δ = 39.86 (dd, J(Rh,P^1) = 124.3 Hz, J(P^1,P^2) = 41.2 Hz, P^2), 30.81 ppm (dd, J(Rh,P^2) = 131.0 Hz, P^1).

4.3.4. Compound **10**, R= Bn

Yield: 95%, IR (cm^{-1}): ν(CN) 2257 (m), ν(SbF$_6$) 652 (s). Anal. Calcd for C$_{47}$H$_{50}$F$_{12}$IrNP$_2$Sb$_2$: C, 41.7; H, 3.7; N, 1.0. Found: C, 41.5; H, 3.5; N, 0.9.

10a, (S_{Ir})–Isomer, 68%: $[\alpha]_D^{25}$= -10.2 (c = 0.46 in CH_2Cl_2). ^{1}H–RMN (400.16 MHz, CD_2Cl_2, 25 ºC): δ = 7.99–7.12 (m, 25H, Ph), 5.93 (s 1H, H_b), 5.17 (s, 1H, H_a), 3.30 (m, 1H, CH*H*Ph), 3.18 (m, 1H, H_{22}), 2.87 (m, 1H, H_{11}), 2.42 (m, 1H, H_{21}), 2.01 (m, 1H, C*H*HPh), 1.62 (t, J = 2.3 Hz, 15H, C_5Me_5), 1.50 ppm (s, 3H, Me). ^{13}C–RMN (100.61 MHz, CD_2Cl_2, 25 ºC): δ = 141.13 (C^5), 137.96–118.84 (30C, Ph), 119.57 (CN), 114.37 (C^4), 102.20 (C_5Me_5), 38.70 (dd, J = 34.2, 7.9 Hz, C^1), 35.33 (d, J = 16.5, 3.3 Hz, C^3), 29.78 (dd, J = 42.0, 12.8 Hz, C^2), 19.12 (Me), 8.54 ppm (C_5Me_5). ^{31}P–RMN (161.96 MHz, CD_2Cl_2, 25 ºC): δ = 35.99 (d, $J(P^2,P^1)$ = 13.1 Hz, P^1), 11.76 ppm (d, P^2).

10b, (R_{Ir})–Isomer, 32%: ^{1}H–RMN (300.10 MHz, CD_2Cl_2, -25 ºC): δ = 5.76 (d, J = 1.7 Hz, 1H, H_b), 5.14 (s, 1H, H_a), 1.59 (s, 15H, C_5Me_5), 1.37 ppm (s, 3H, Me). ^{31}P–RMN (121.48 MHz, CD_2Cl_2, -25 ºC): δ = 35.13 (d, $J(P^2,P^1)$ = 9.5 Hz, P^1), 25.04 ppm (d, P^2).

*4.3.5. Compound **11**, R= Cy*

Yield: 90%. IR (cm^{-1}): ν(CN) 2254 (m), ν(SbF_6) 652 (s). Anal. Calcd for $C_{46}H_{54}F_{12}IrNP_2Sb_2$: C, 41.0; H, 4.0; N, 1.0. Found: C, 41.0; H, 4.1; N, 0.9.

11a, (S_{Ir})–Isomer, 67%: $[\alpha]_D^{25}$= -19.1 (c = 0.67 in CH_2Cl_2). ^{1}H–RMN (400.16 MHz, CD_2Cl_2, 25 ºC): δ = 7.93–7.31 (m, 20H, Ph), 5.83 (bs, 1H, H_b), 5.06 (bs, 1H, H_a), 3.34 (dt, J = 51.7, 11.6 Hz, 1H, H_{22}), 2.43 (m, 1H, H_{21}), 2.39 (m, 1H, H_{11}), 1.73–0.76 (m, 11H, Cy), 1.56 (t, J = 2.3 Hz, 15H, C_5Me_5), 1.40 ppm (t, J = 1.3 Hz, 3H, Me). ^{13}C–RMN (100.61 MHz, CD_2Cl_2, 25 ºC): δ = 140.88 (C^5), 135.02–120.64 (24C, Ph), 119.91 (CN), 114.46 (C^4), 102.10 (C_5Me_5), 42.28–25.52 (6C, Cy), 37.35 (dd, $J(P,C)$ = 13.4, 4.3 Hz, C^1), 27.07 (m, C^2), 19.10 (Me), 8.49 ppm (C_5Me_5). ^{31}P–RMN (161.96 MHz, CD_2Cl_2, 25 ºC): δ = 40.46 (d, $J(P^2,P^1)$ = 13.0 Hz, P^1), 14.60 ppm (d, P^2).

11b, (R_{Ir})–Isomer, 33%: ^{1}H–RMN (400.16 MHz, CD_2Cl_2, -10 ºC): δ = 5.86 (bs, 1H, H_b), 5.11 (bs, 1H, H_a), 3.50 (m, 1H, H_{22}), 2.87 (m, 1H, H_{21}), 2.79 (m, 1H, H_{11}), 1.53 (t, J =

2.2 Hz, 15H, C_5Me_5), 1.35 ppm (s, 3H, Me). ^{31}P–RMN (161.96 MHz, CD_2Cl_2, 20 ºC): δ = 28.51 (d, $J(P^2,P^1)$ = 13.9 Hz, P^1), 20.51 ppm (d, P^2).

4.3.6. Compound 12

Yield: 82%. IR (cm^{-1}): ν(CN) 2254 (m), ν(SbF_6) 654 (s). Anal. Calcd for $C_{45}H_{48}F_{12}IrNP_2Sb_2$: C, 40.7; H, 3.6; N, 1.0. Found: C, 41.3; H, 3.3; N, 1.1.

12a, (S_{Ir})–Isomer, 53%: ^{1}H–RMN (300.10 MHz, CD_2Cl_2, 25 ºC): δ = 7.95–7.15 (m, 20H, Ph), 6.15 (m, 1H, H_5), 5.97 (bs, 1H, H_b), 5.30 (bs, 1H, H_a), 4.89 (dd, J = 5.3, 2.7 Hz, 1H, H_6), 3.45 (s, 1H, H_1), 3.30 (m, 1H, H_2), 3.11 (s, 1H, H_4), 3.08 (m, 1H, H_3), 2.36 (m, 1H, H_{71}), 2.18 (m, 2H, H_4, H_{72}), 1.68 (s, 3H, Me), 1.61 ppm (t, J = 2.4 Hz, 15H, C_5Me_5). ^{13}C–RMN (75.50 MHz, CD_2Cl_2, 25 ºC): δ = 141.17 (C^{10}), 140.88 (d, J = 7.7 Hz, C^5), 134.96–121.73 (24C, Ph), 130.29 (C^6), 126.25 (CN), 114.78 (C^9), 101.03 (t, J = 1.6 Hz, C_5Me_5), 53.24 (m, C^7), 51.11 (dd, J = 33.9, 14.7 Hz, C^3), 45.41 (dd, J = 42.5, 14.8 Hz, C^2), 43.60 (dd, J = 8.3, 6.6 Hz, C^1), 40.89 (dd, J = 12.2, 6.8 Hz, C^4), 19.10 (Me), 8.78 ppm (C_5Me_5). ^{31}P–RMN (121.48 MHz, CD_2Cl_2, 25 ºC): δ = 6.00 (d, $J(P^2,P^1)$ = 27.0 Hz, P^1), -1.41 ppm (d, P^2).

12b, (R_{Ir})–Isomer, 47%: ^{1}H–RMN (300.10 MHz, CD_2Cl_2, 25 ºC): δ = 6.78 (m, 1H, H_5), 6.15 (m, 1H, H_6), 6.07 (s, 1H, H_b), 5.46 (s, 1H, H_a), 3.45 (m, 1H, H_1), 3.26 (s, 1H, H_3), 2.88 (s, 1H, H_4), 2.53 (m, 1H, H_2), 2.01 (m, 1H, H_{72}), 1.65 (t, J = 2.5 Hz, 15H, C_5Me_5), 1.59 (s, 3H, Me), 0.41 ppm (d, J = 9.4 Hz, 1H, H_{71}). ^{13}C–RMN (75.50 MHz, CD_2Cl_2, 25 ºC): δ = 142.03 (d, J = 7.8 Hz, C^6), 141.40 (C^{10}), 114.86 (C^9), 133.58 (C^5), 126.35 (CN), 101.28 (t, J = 1.6 Hz, C_5Me_5), 52.58 (C^7), 49.08 (dd, J = 41.5, 16.3 Hz, C^2), 47.26 (dd, J = 33.4, 13.5 Hz, C^1), 43.08 (dd, J = 9.6, 7.8 Hz, C^3), 40.49 (dd, J = 11.4, 5.4 Hz, C^4), 19.13 (Me), 8.79 ppm (C_5Me_5). ^{31}P–RMN (121.48 MHz, CD_2Cl_2, 25 ºC): δ = 5.94 (d, $J(P^2,P^1)$ = 27.5 Hz, P^2), –1.61 ppm (d, P^1).

4.4. Epimerisation reactions

Mixtures of *S* and *R* at metal epimers were dissolved in acetone. After stirring at RT for 1 hour (rhodium complexes **7** and **8**) or refluxing for 6 hours (iridium complexes **10** and **11**) the solution was concentrated to about 1 mL and then hexane (10 mL) was added. The resulting yellow solids were characterised by NMR as the corresponding diastereopure *S* at metal epimers.

On the other hand, after refluxing for 6 hours in acetone 56/44 (rhodium complex **9**) or 53/47 (iridium complex **12**) molar ratio mixtures of the corresponding *S* and *R* at metal epimers, diastereomeric mixtures with 40% d. e. in favour of the *S* at metal epimer were recovered, in both cases.

4.5. Stoichiometric catalytic reactions

At room temperature, to a dichloromethane solution of the corresponding diastereopure methacrylonitrile complex **7a**, **8a**, **10a** and **11a** or 70/30 molar ratio mixtures of the **9a/9b** and **12a/12b** complexes (4 mL, ca. 7.5×10^{-2} molL^{-1}), five equivalents of nitrone were added. The solution was stirred for 3 h and then an excess of ^{n}Bu$_4$NBr (ca. 5 equiv) in CH$_2$Cl$_2$ (1 mL) was added. The solvent was evaporated under vacuum to dryness and the residue was extracted with diethyl ether/CH$_2$Cl$_2$: 5/1 (3 × 5 mL). Solvents of the combined extracts were evaporated and the resulting colourless oil was analysed and characterised by NMR and HPLC techniques.

4.6. Recycling experiments

To diastereopure (S_{Rh},R_C)–[(η^5–C$_5$Me$_5$)Rh{(*R*)–Cyphos}(NC(Me)C=CH$_2$)] [SbF$_6$]$_2$ (**8a**, 93.5 mg, 0.075 mmol) in CH$_2$Cl$_2$ (4 mL), 3,4–dihydroisoquinoline *N*–oxide 55.2 mg (0.375 mmol) in CH$_2$Cl$_2$ (1 mL) was added. The resulting solution was stirred for 3 h, at RT, and then vacuum–evaporated to dryness. The residue was washed with an Et$_2$O/CH$_2$Cl$_2$, 9/1, v/v mixture (10 × 7 mL) to eliminate the excess of nitrone. To the remaining solid, dissolved in CH$_2$Cl$_2$ (4 mL), methacrylonitrile (125.7 μL, 1.500 mmol)

was added. After stirring for 4 h at 0 ºC, the solution was concentrated under reduced pressure to dryness. The residue was extracted with an Et_2O/CH_2Cl_2, 9/1, v/v mixture (10×7 mL) and the obtained solution was concentrated under vacuum to dryness. Yield and enantiomeric purity of this solid was determined by the usual methods. The remaining solid after the extraction, which consisted of **8a**/**8b** mixtures, was dissolved in CH_2Cl_2 (4 mL) and the solution stirred at room temperature to complete epimerization to **8a** (about 3 hours). Addition of 3,4–dihydroisoquinoline *N*–oxide (55.2 mg, 0.375 mmol) to this solution initiated the next catalytic reaction.

*4.7. X-ray Structure Determination of compound **7a***

X-ray diffraction data were collected at 100(2) K on a Bruker SMART APEX CCD area detector diffractometer with graphite-monochromated Mo Kα radiation ($\lambda = 0.71073$ Å) using narrow ω rotations (0.3°). Intensities were integrated with SAINT–PLUS program[21] and corrected from absorption effects with SADABS.[22] The structure was solved by direct methods with SHELXS–2013[23] and refined, by full–matrix least–squares method on F^2, with SHELXL–2013,[24] included in WinGX package.[25] All non–hydrogen atoms allowed anisotropic thermal motion. Hydrogen atoms were observed in Fourier differences maps and refined with a riding model from calculated. Additionally to the internal configuration reference of the (*R*)–Benphos ligand, the Flack parameter was refined as a check of the correct absolute structure determination.[26] Information concerning crystallographic data collection and structure refinement is summarized in Supplementary Material. CCDC–1443435 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data request/cif.

Acknowledgements

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