Development of Dirhodium(II)-Catalyzed Generation and Enantioselective 1,3-Dipolar Cycloaddition of Carbonyl Ylides

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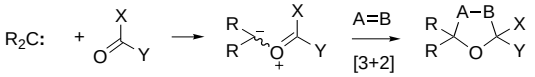
Abstract: Catalytic, enantioselective, tandem carbonyl ylide formation/cycloaddition of 2-diazo-3,6-diketoester **2** with the use of dirhodium tetrakiscarboxylate and tetrakisbinaphtholphosphate catalysts to give the cycloadducts **3** in good yields and up to 90% *ee* is described.

Keywords: asymmetric catalysis · catalysts · cycloaddition · diazo compounds · rhodium

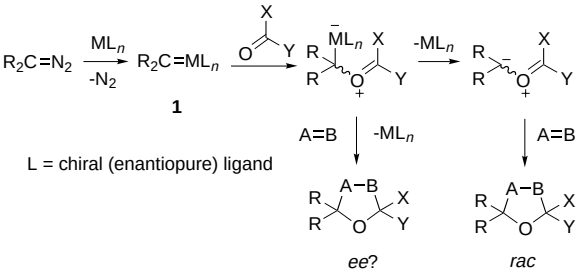
Introduction

There are currently few methods to achieve catalytic enantioselective 1,3-dipolar cycloadditions, despite the potential utility of such asymmetric transformations.[1] Carbonyl ylides are usually non-isolable reactive intermediates whose principal synthetic uses are in 1,3-dipolar cycloadditions. Of the various methods for carbonyl ylide formation, the interaction of a carbene with the oxygen atom of a carbonyl group is particularly attractive because of its apparent simplicity (Scheme 1).[2]



Scheme 1. Carbonyl ylide formation/cycloaddition.

The synthetic utility of free carbenes in such an ylide-forming process is limited partly by their methods of generation (thermally, photochemically or under basic conditions), and also by their high reactivity and lack of selectivity with functionalised organic compounds. It is often preferable to use metal–carbene complexes **1** (Scheme 2) in which the metal, and the ligands with which it is usually associated, can potentially influence the reactivity of the carbene. Metal–carbene complexes are themselves often transient intermediates. One good way of generating metal–carbene complexes as intermediates is the reaction of a diazo (often an α-diazocarbonyl) compound with a metal–ligand system (the metal is often rhodium or copper).[3] This process has been extensively examined in the context of tandem carbonyl ylide formation/cycloaddition by Ibata and, particularly, Padwa and has become an important method for the synthesis of oxacycles.[4] The transformation is attractive because of the rapid increase in molecular complexity, and good levels of diastereoselectivity can be observed. One intriguing question relates to the possibility of achieving an enantioselective cycloaddition by using a chiral catalyst (Scheme 2).



Scheme 2. Metal-catalysed carbonyl ylide formation/cycloaddition.

Although significant progress has been made in transformations of diazocarbonyl compounds involving enantioselective C=C, C–H or X–H (X = N, Si) insertions using chiral, non-racemic transition metal-based catalysts,[3, 5] at the outset of our studies there were no reported examples of enantioselective, tandem carbonyl ylide formation/cycloaddition. Unlike enantioselective insertion, in which an intermediate

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Supporting information for this article is available on the WWW under http://wiley-vch.de/home/chemistry/ or from the author. Preparation of **22** and spectral characterisation (^{13}C NMR spectra) of **2**, **3**, **5**, **16**, **17b**, **28**, **30**–**33**, **35**, **36**, **38**, and **39** (26 pages).

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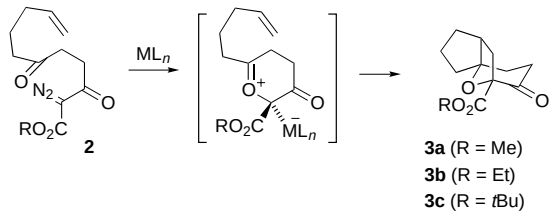
metal carbene complex can directly exert an influence on selectivity, it could be argued that once an ylide is formed the catalyst is not involved in the subsequent cycloaddition and asymmetric induction would be unlikely. However, prior to our work, Padwa and co-workers had observed rhodium(II)-catalyst-dependent changes in regiochemistry during intramolecular cycloaddition following carbonyl ylide formation.[6] Also, there were scattered reports of enantioselective rearrangements, based on transition-metal catalysis, involving other types of ylides from diazo compounds, which could also be interpreted as implying catalyst association with the ylide during the rearrangement step.[7] In this paper we detail our studies on the realisation of enantioselective tandem carbonyl ylide formation/cycloaddition,[8] which have involved the synthesis and examination of a number of new chiral rhodium(II) catalysts to generate cycloadducts in up to 90% *ee* in this emerging asymmetric process.

Results and Discussion

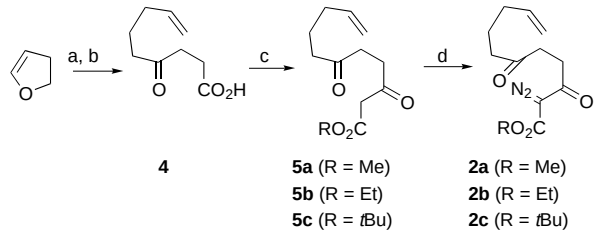
Our choice of substrate to examine this chemistry was influenced by the consideration that asymmetric induction might depend upon the rate of cycloaddition of a carbonyl ylide, since a potential requirement for asymmetric induction could be that cycloaddition is faster than catalyst decomplexation from the ylide. We therefore first examined a 2-diazo-3,6-diketoester **2** (Scheme 3) designed to undergo intramolecular cycloaddition with a simple terminal alkene, as a



Scheme 3. Intramolecular carbonyl ylide formation/cycloaddition.

closely related system to **2** (with $CO_2R = H$) had previously been shown to undergo intramolecular cycloaddition faster than intermolecular cycloaddition of the ylide with the highly reactive dipolarophile dimethyl acetylenedicarboxylate (DMAD).[9] Expected advantages of studying an α-diazo-β-ketoester of this type were ease of synthesis by diazo transfer, combined with stability, storage and ease of handling of a doubly stabilised (by ester and keto groups) diazo substrate, and ability to vary the ester group. Also, cycloaddition regio- and (*exo*-, *endo*-) stereochemistry would be unambiguous, and related systems could find utility in the synthesis of biologically active natural product classes.[4]

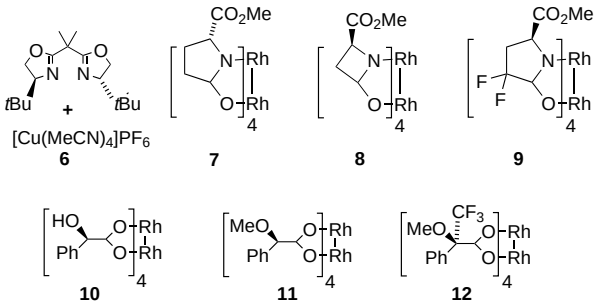
2-Diazo-3,6-diketoesters **2** (R = alkyl) were prepared according to Scheme 4. 4-Oxo-8-nonenoic acid (**4**) was originally made (41%) following the published procedure of pentenyl Grignard addition to succinic anhydride;[10] however, a significant amount (ca. 20%) of 4,4-dipentenyl-γ-butyrolactone was also observed. The latter compound arose from a second addition of the Grignard reagent to the intermediate



Scheme 4. Synthesis of cycloaddition substrate **2**. Reagents and conditions: a) *t*BuLi, $CH_2{=}CH(CH_2)_3I$, THF, $-78\,^\circ C$ to $25\,^\circ C$; b) Jones' reagent, THF, $25\,^\circ C$; c) carbonyldiimidazole, THF, $0\,^\circ C$, then $Mg(O_2CCH_2CO_2R)_2$, THF, $25\,^\circ C$, then H_3O^+; d) 4-(NHAc)$C_6H_4SO_2N_3$, Et_3N, MeCN, $25\,^\circ C$.

ketone followed by ring closure. Due to the inefficiency of this method, an alternative procedure was devised. A range of 4-ketoalkanoic acids have been prepared by Meyers and co-workers by alkylation of lithiated 2,3-dihydrofuran followed by hydrolysis/oxidation with Jones' reagent.[11] Using 5-iodopent-1-ene as the alkylating agent, this two-step procedure gave keto acid **4** in an improved 68% yield. Homologation of the keto acid **4** to 3,6-diketoesters **5** was best achieved by a modified version of the Masamune procedure (58–92%),[12] in which the magnesium salts of monoalkyl malonates were prepared using Bu_2Mg rather than $Mg(OEt)_2$.[13] Diazo transfer then afforded the cycloaddition precursors **2** in good to excellent yields (70–91%).

The viability of the substrates **2** to undergo the desired ylide formation/cycloaddition process was established by treatment with rhodium(II) acetate in CH_2Cl_2 heated under reflux (60–80% yields of cycloadducts **3**); these racemic cycloadducts were also used for establishing enantiomeric purity determination assays (vide infra). The use of a copper catalyst **6** ($[Cu(MeCN)_4]PF_6$ in combination with a enantiopure



bisoxazoline ligand), as used by Doyle to affect enantioselective cyclopropanation,[14] and more recently in enantioselective 2,3-sigmatropic rearrangements of oxonium and iodonium ylides,[15] proceeded only sluggishly in CH_2Cl_2 heated under reflux overnight to deliver optically inactive cycloadduct **3c** (25% yield, 100% based on recovered **2**); the use of copper-based catalysts was not further pursued. At this stage, representatives of the known classes of chiral rhodium(II) catalysts, selected for their varying electronic and steric properties and ability to induce enantioselectivity in other diazocarbonyl transformations,[3, 5] were screened with the cycloaddition substrates **2**, generally both in chlorinated and

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(where the catalyst was sufficiently soluble) hydrocarbon solvents.

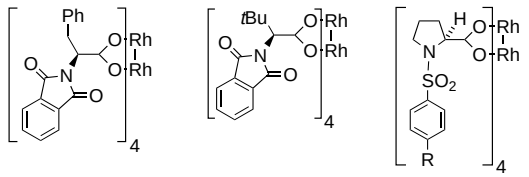
Although carboxamidate catalysts might be anticipated to be somewhat unreactive towards diazo decomposition with doubly stabilised diazo compounds such as **2**, the well-known commercially available glutamic-acid-derived catalyst $[Rh_2\{(R)\text{-mepy}\}_4]$ (**7**; mepy = methyl 2-pyrrolidine 5-carboxylate anion),[3, 16] the more reactive azetidine-based catalyst **8**[17] and the difluorinated catalyst **9**[18] all generated cycloadduct **2**, albeit with no optical activity. The mandelic-acid-derived catalysts **10** and **11**, were two of the first reported examples of chiral Rh^{II} catalysts,[19, 20] the former generating the highest levels of asymmetric induction (45% *ee*) in a study by McKervey et al. of enantioselective N–H insertion.[21] Of the range of chiral carboxylate catalysts that were screened (seven examples) in enantioselective Si–H insertion by Moody and co-workers, the highest level of enantioselectivity (31% *ee*) was obtained with Rh^{II} catalyst **12**, which is derived from Mosher's acid.[22] All three of these oxygenated carboxylate-ligand-containing catalysts gave the cycloadduct **3c** in generally high yields, and importantly asymmetric induction was observed, but at a low level (Table 1, entries 1–6); there was no significant solvent effect on *ee* with these catalysts. One anomalous yield (48%) was obtained from the use of **10** in hexane (entry 2); this could result from the poor solubility of the catalyst in this solvent.

Table 1. Effect of Rh–carboxylate catalysts **10**–**19** in the cycloaddition of **2c**.

Entry	Catalyst	Solvent	T [°C]	**3c** yield [%]	**3c** *ee* [%][a]
1	**10**	CH_2Cl_2	25	93	–11
2	**10**	hexane	25	48	–9
3	**11**	CH_2Cl_2	25	97	–16
4	**11**	hexane	25	92	–22
5	**12**	CH_2Cl_2	25	98	–17
6	**12**	hexane	25	95	–9
7	**13**	CH_2Cl_2	25	87	–28
8	**13**	hexane	25	55	–21
9	**14**	CH_2Cl_2	25	72	–23
10	**14**	hexane	69[b]	86	–20
11	**14**	Et_2O	25	60	–14
12	**15a**	hexane	25	59	38
13	**15b**	CH_2Cl_2	25	86	10
14	**15b**	hexane	25	77	52
15	**15b**	hexane	43	84	48
16	**15b**	hexane	69	89	42
17	**15b**	hexane	0	74	51
18	**15b**	hexane	–7	55	48
19	**16**	CH_2Cl_2	25	81	13
20	**16**	hexane	25	75	31
21	**17a**	CH_2Cl_2	25	43	–17
22	**17a**	hexane	25	60	–34
23	**17b**	CH_2Cl_2	25	87	–16
24	**17b**	hexane	25	65	–32
25	**18**	CH_2Cl_2	25	71	–20
26	**18**	hexane	25	51	–36
27	**19**	CH_2Cl_2	25	55	–22
28	**19**	hexane	25	65	–22

[a] *ee*s were determined after conversion from the *t*Bu ester **3c** to the methyl ester **3a** by hydrolysis/esterification [trifluoroacetic acid (TFA), CH_2Cl_2 then MeOH, *para*-toluenesulfonic acid (*p*-TSA)] and ^1H NMR analysis of the split methoxy signal using praseodymium tri[3-(heptafluoropropylhydroxymethylene)-(+)-camphorate] [Pr(hfc)$_3$]. Negative values correspond to enrichment in (–)-cycloadduct **3c**. [b] No reaction at 25 °C.

In 1990 Hashimoto, Watanabe and Ikegami published their first examples of enantioselective C–H insertion of carbenoid intermediates derived from α-diazo-β-ketoesters and catalysed by chiral Rh^{II} carboxylates, the latter generally prepared from *N*-phthaloyl amino acids.[23] Since this initial report, a series of studies have been described by the Ikegami/Hashimoto groups developing this approach and demonstrating the utility of the products.[24] As two of the most impressive catalysts in terms of enantioselectivity are derived from phenylalanine and *tert*-leucine, we selected these catalysts (**13** and **14**) to be screened in the tandem carbonyl ylide cyclisation/cycloaddition as representative examples of this group of Rh^{II} complexes; however, they were found to be only weakly enantioselective (up to 28% *ee*, Table 1, entries 7–11).

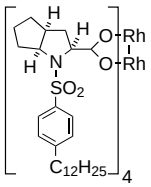


13 **14** **15a** (R = *t*Bu) **15b** (R = $C_{12}H_{25}$)

Proline-derived catalysts, initially studied by McKervey,[25] were found by Davies and co-workers to deliver excellent *ee*s (up to 98% *ee*) in a series of cyclopropanations.[26] Examination of the tandem carbonyl ylide formation/cycloaddition process with the prolinate catalyst $[Rh_2\{(S)\text{-dosp}\}_4]$ (**15b**; dosp = *N*-(*p*-dodecylphenyl)sulfonylprolinate) gave only a low level of enantioselection in CH_2Cl_2 (Table 1, entry 13). However, in line with other asymmetric transformations with **15b**,[26] a significant increase in *ee* was observed in hydrocarbon solvent (Table 1 entry 14) relative to CH_2Cl_2. Unlike most of the catalyts studied, **15b** is fully hydrocarbon soluble, due to the dodecyl substituent. The partially hydrocarbon soluble (at 25 °C) catalyst **15a** was not as effective (entry 12). Davies and co-workers have observed a major effect of ester group size in asymmetric cyclopropanations that make use of catalyst **15b** with ester-substituted vinyldiazomethanes (methyl esters giving the highest levels of enantioselectivity).[26] However, similar *ees* to those of the *t*Bu-substituted ester **2c** in hexane were found with the Me- and Et-substituted 2-diazo-3,6-diketoesters **2a**,**b** (e.g., at room temperature 86% yield, 48% *ee* and 82% yield, 52% *ee*, respectively). Yields of the cycloadduct **3c** formed by using catalyst **15b** in hexane steadily improved as the reaction was carried out at increasing temperatures; however, there was a slight erosion in *ee* (entries 15 and 16). Cooling the reaction to 0 °C resulted in little change in *ee* or yield (entry 17); below 0 °C yield was eroded (entry 18) and no cycloadduct was obtained at –14 °C. The Me- and Et-substituted 2-diazo-3,6-diketoesters **2a**,**b** showed slightly greater variation of *ee* with temperature (for **2a** at 69 °C, 96% yield, 48% *ee* and at 0 °C, 65% yield, 33% *ee*; for **2b** at 69 °C, 90% yield, 29% *ee* and at 0 °C, 63% yield, 52% *ee*), room temperature being optimal for both substrates. This led to *t*Bu ester **2c**, rather than the corre-

sponding Me and Et esters **2a**,**b**, being examined in the bulk of the studies.

With catalyst **15** as an initial lead, modification of the prolinate framework was probed by an examination of catalysts **16**,[27] **17**,[28] **18**[29] and **19**.[30] A similar solvent



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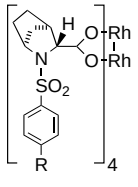
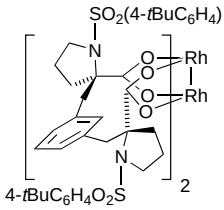


17a (R = *t*Bu)
17b (R = $C_{12}H_{25}$)



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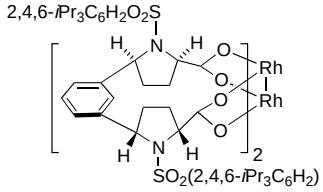
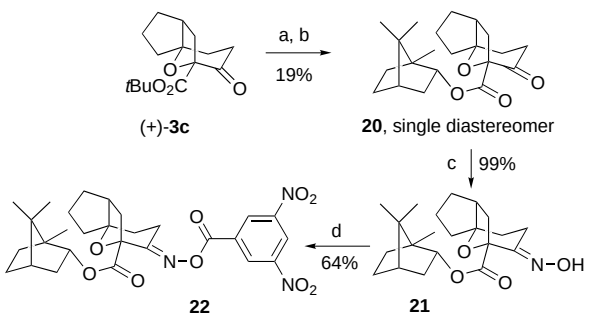


19

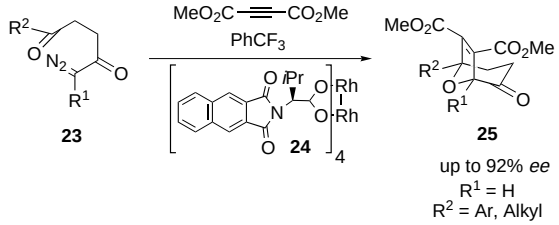
dependency on *ee* to that observed with **15b** was found with **16** and **17** (Table 1, entries 19 to 24); *ee*s were better in hydrocarbon solvent. The ligand in catalyst **18** was originally designed by Davies to form a conformationally constrained catalyst with an up-down up-down arrangement of the arylsulfonyl groups, thus allowing the effect of ligand alignment in vinyl–carbenoid cyclopropanations in polar and nonpolar solvents to be studied.[29] To the extent that the *ee*s converge slightly in CH_2Cl_2 and hexane with ligand **18** (entries 25 and 26) relative to **15b** (entries 13 and 14), then favourable ligand aligment using **15b** in hexane may also play a role in the asymmetric dipolar cycloaddition process. Similar results were obtained in both hexane and CH_2Cl_2 when **19** was used as the catalyst (entries 27 and 28). Since the favoured solvent for **19** in cyclopropanations has been found to be CH_2Cl_2,[30] the observation in the present study of identical enantioselectivities in the two solvents suggests that hexane is inherently the superior solvent for enantioselective cycloaddition with the prolinate-type catalysts, for which **15b** gave the highest *ee*.

It was considered important to establish that the *ee* in the reaction with these catalysts arises entirely due to the cycloaddition process and is not affected by possible enantiomer-selective destruction of the cycloadduct **3** by the catalyst. This was proven by stirring enantioenriched **3c** with catalyst **15b** in CH_2Cl_2 or hexane at 25 °C for 12 hours; this resulted in essentially quantitative recovery of the cycloadduct **3c**, with unchanged *ee*. The absolute configuration of the predominant cycloadduct enantiomer (+)-**3c** formed by using α-diazo-β-ketoester **2c** and catalyst **15b** was also determined, as shown in Scheme 5. Thus, hydrolysis of cycloadduct **3c** with trifluoroacetic acid (TFA) followed by esterification with (1*S*)-*endo*-(−)-borneol and recrystallisation gave the major diastereomer borneol ester **20**. Condensation of the borneol ester **20** with hydroxylamine gave the oxime **21** and finally reaction with 3,5-dinitrobenzoyl chloride gave derivative **22** suitable for crystallographic analysis.[31]



Scheme 5. Determination of the absolute configuration of cycloadduct (+)-**3c**. Reagents and conditions: a) TFA, CH_2Cl_2, 25 °C, 1 h; b) i) (−)-borneol, DMAP, DCC, CH_2Cl_2, 25 °C, 18 h; ii) recrystallisation from cyclohexane; c) $NH_2OH.HCl$, NaOAc, MeOH, 25 °C, 15 h; d) 3,5-dinitrobenzoyl chloride, pyridine, Et_2O, 25 °C, 2 h.

During the course of our studies,[8] research groups led by Doyle,[32] Ibata[33] and Hashimoto[34] reported conceptually related (but intermolecular) asymmetric carbonyl ylide cycloadditions. The asymmetric induction in these cycloadditions was low (<30 % *ee*), aside from the work of Hashimoto who used α-diazoketones with DMAD as the dipolarophile for which *ee*s up to 92 % were reported (Scheme 6, $R^1 = H$, $R^2 =$ Ph, absolute sense of predominant asymmetric induction not



Scheme 6. Cycloadditions with DMAD.

determined).[34a] Applying the optimised catalyst–solvent combination for intermolecular cycloaddition of α-diazoketones with DMAD reported by Hashimoto[34a] (catalyst **24**, $PhCF_3$ as solvent) to 2-diazo-3,6-diketoester **2c** at 25 °C resulted in only essentially racemic cycloadduct **3c** (90 % yield, 1 % *ee*). Furthermore, cycloadduct **25** ($R^1 = CO_2Et$, $R^2 = Me$)[35] was obtained in only 33 % *ee* under the same conditions in the reaction of 2-diazo-3,6-diketoester **23** ($R^1 = CO_2Et$, $R^2 = Me$)[35] with DMAD [α-diazoketone **23** ($R^1 = H$, $R^2 = Me$) gave cycloadduct in 80 % *ee*].[34a] These last results indicate that *ee* is rather sensitive to variation in the electronic structure of the dipole.

As a maximum *ee* of 52 % was observed from the screening of Rh^{II}–carboxylate catalysts (Table 1), it was considered that an alternative class of catalysts should be investigated. In seeking to develop more efficient catalysts for asymmetric carbonyl ylide formation/cycloaddition, we were attracted to the reports in 1992 by Pirrung[36] and McKervey[37] concerning binaphtholphosphate (bnp) catalysts $[Rh_2\{(R)\text{-bnp}\}_4]$ (**26**) and $[Rh_2\{(S)\text{-bnp}\}_2(O_3CH)_2]\cdot 5H_2O$ for diazocarbonyl decompo-

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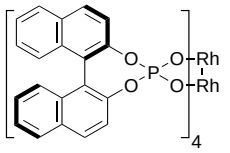


[Rh_2{(*R*)-bnp}$_4$] (**26**)

sition. C–H insertion and cyclopropanation were among the asymmetric processes investigated (up to 60% *ee*). More recently Müller and co-workers have included catalyst **26** in studies of asymmetric aziridination (up to 73% *ee*) and enantioselective allylic amination (31% *ee*).[38]

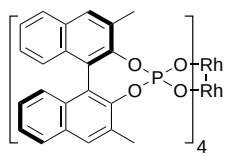
Initial investigation of Pirrung's structurally well-defined D_4-symmetric catalyst [Rh_2{(*R*)-bnp}$_4$] (**26**) with 2-diazo-3,6-diketoester **2c** in hexane at 25 °C gave an immediate improvement in *ee* of the cycloadduct (+)-**3c** (64% *ee*, Table 2, entry 1) compared with [Rh_2{(*S*)-dosp}$_4$] (**15b**; 52% *ee*), even though **26** was only partially soluble in hexane at 25 °C. Interestingly, asymmetric induction was maintained in CH_2Cl_2 at 25 °C (65% *ee*, entry 2); this compares with 10% *ee* previously obtained by using **15b** in CH_2Cl_2 (Table 1, entry 13). Whilst binaphthol catalyst **26** remained soluble in CH_2Cl_2 at 0 °C, no improvement in *ee* was observed (64%, Table 2, entry 3). Good solubility was also observed in benzene at 25 °C, although *ee* was poor (33%, entry 4). The results with binaphthol catalyst **26** prompted a study of the effects of structural variation of the binaphthyl core on enantioselectivity.

Table 2. Effect of binaphtholphosphate-type catalysts **26**–**28**, **33**, **36** and **39** in the cycloaddition of **2c**.

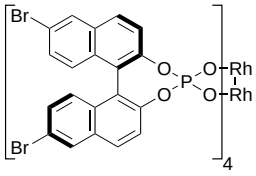
Entry	Catalyst	Solvent	T [°C]	**3c** yield [%]	**3c** *ee* [%][a]
1	**26**	hexane	25	65	64
2	**26**	CH_2Cl_2	25	83	65
3	**26**	CH_2Cl_2	0	55	64
4	**26**	benzene	25	55	33
5	**27**	CH_2Cl_2	25	50	7
6	**27**	benzene	25	30	26
7	**28**	hexane	25	34	66
8	**28**	CH_2Cl_2	25	67	58
9	**28**	CH_2Cl_2	0	36	61
10	**33**	CH_2Cl_2	25	80	68
11	**33**	hexane	25	76	81
12	**33**	hexane	0	81	88; 89[b] 88[c]
13	**33**	hexane	−15	66	90[b]
14	**36**	CH_2Cl_2	25	47	55[c]
15	**36**	hexane	25	65	75[c]
16	**36**	hexane	0	35	74[c]
17	**39**	CH_2Cl_2	25	60	−59[c]
18	**39**	hexane	25	66	−77[c]
19	**39**	hexane	0	42	−80[c]

[a] *ee*s determined by using the method described in Table 1, footnote [a]. [b] *ee*s determined on the benzyl oxime ether (*O*-benzyl hydroxylamine hydrochloride, NaOAc, MeOH) of the methyl ester by HPLC analysis (Daicel Chiralpak AD, 10% EtOH/hexane) of the major geometric isomer. [c] *ee*s determined directly on **3c** by GC analysis (CP Chirasil Dex-CD and Cydex-β (entry 12), 140 °C isotherm). Negative values correspond to enrichment in (−)-cycloadduct **3c**.

Substitution at the 3,3′-positions was first examined using dimethylbinaphthol catalyst **27**,[39] which was prepared (79%) by an analogous procedure[36] to **26** from [$Rh_2(OAc)_4$] by ligand exchange with the known 3,3′-dimethylbinaphtholhydrogen phosphate.[40] However, reaction of [Rh_2{(*R*)-dmbnp}$_4$] (**27**; dmbnp = dimethylbinaphtholphosphate)



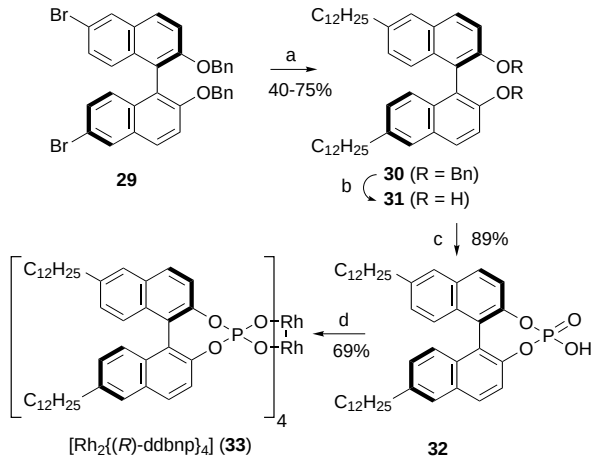
[Rh_2{(*R*)-dmbnp}$_4$] (**27**)



[Rh_2{(*R*)-dbbnp}$_4$] (**28**)

with 2-diazo-3,6-diketoester **2c** led to no cycloadduct in hexane, a very low *ee* (7%) of (+)-**3c** in CH_2Cl_2 (Table 2, entry 5) and a poor result in benzene (entry 6), possibly due to steric congestion at the axial binding sites on the dirhodium core; this (in CH_2Cl_2) might also facilitate catalyst release to give the free ylide for cycloaddition.

Substitution at the 6,6′-positions has been a successful tactic to alter asymmetric induction with binaphthyl-based catalysts.[41] [Rh_2{(*R*)-dbbnp}$_4$] (**28**; dbbnp = dibromobinaphtholphosphate), available from 6,6′-dibromobinaphtholhydrogen phosphate,[42] induced similar *ee*s to **26** (entries 7–9). The yield of reaction in hexane (entry 7) was most likely low due to the common problem of poor catalyst solubility in hexane, which also resulted in a long reaction time (15 h as opposed to 0.5 h in CH_2Cl_2). With the primary aim of investigating a more hydrocarbon-soluble catalyst, **33** was synthesised according to Scheme 7.



Scheme 7. Synthesis of catalyst **33**. Reagents and conditions: a) $C_{12}H_{25}MgBr$, $NiCl_2$, $Ph_2P(CH_2)_3PPh_2$ (1 mol%), Et_2O, reflux, 48 h; b) TMSCl, NaI, MeCN, $PhCH_3$, 40 °C, 2 h (89%); c) $POCl_3$, pyridine, 25 °C, 1 h, then H_2O, $NaHCO_3$; d) [$Rh_2(OAc)_4$], PhCl, reflux, 6 h.

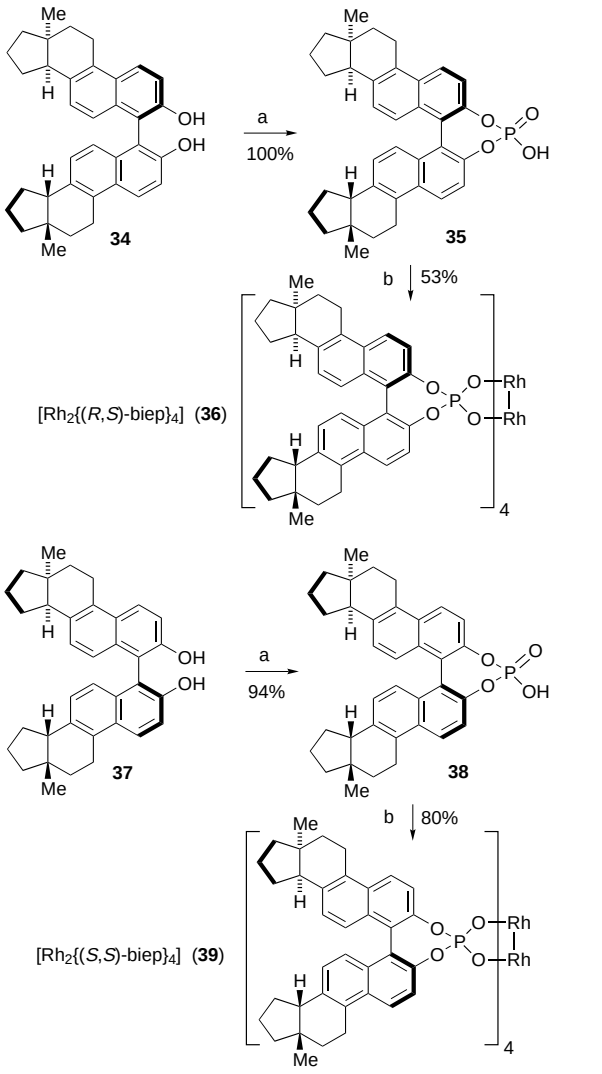
The known bis-ether **29**[43] was cross-coupled[44] with commercially available dodecylmagnesium bromide (40–75%, Scheme 7). Deprotection of the resultant didodecylbis-ether **30** using TMSI[45] gave diol **31** (89%). Formation of the acid **32** (91%) from the diol **31** under standard conditions followed by ligand exchange[46] gave [Rh_2{(*R*)-ddbnp}$_4$] (**33**, 69%; ddbnp = didodecylbinaphtholphosphate). Although only a slight rise in the *ee* of (+)-**3c** was noted with **33** in CH_2Cl_2 at 25 °C (Table 2, entry 10) relative to **26**, the new catalyst was significantly more effective in hexane (81% *ee*, entry 11). Moreover, catalyst solubility and activity were

maintained in hexane at 0 °C and asymmetric induction rose to give the cycloadduct (+)-**3c** in 81% yield and 89% *ee* (entry 12). A similar *ee* (90%) was observed on conducting the reaction at −15 °C (entry 13), whereas reaction at −30 °C was very slow and gave a complex product mixture from which no cycloadduct was isolable.

It was considered important to probe the effect on enantioselectivity of a smaller ester substituent in the cycloadditions with the phosphate catalysts, since they might not show the same insensitivity to ester variation as the prolinate catalysts. With $[Rh_2\{(R)\text{-dmbnp}\}_4]$ (**27**), reaction with methyl ester **2a** was examined and the enantioselectivities in CH_2Cl_2 (4% *ee*, 76% yield) and C_6H_6 (26% *ee*, 73% yield) were found to be very similar to those obtained with **2c** (Table 2, entries 5 and 6). However, reaction of methyl ester **2a** under catalysis by $[Rh_2\{(R)\text{-ddbnp}\}_4]$ (**33**) at 25 °C resulted in a dramatic decrease in enantioselectivity in both hexane (20% *ee*, 72% yield) and CH_2Cl_2 (7% *ee*, 77% yield), relative to that observed when using precursor **2c** (81% *ee* and 68% *ee*, respectively, Table 2, entries 10 and 11). This was further emphasised by a reversal in the predominant sense of asymmetric induction when C_6H_6 was used as the solvent with **2a** and **33** at 25 °C (−10% *ee*, 57% yield); this last result is consistent with the enantioselectivity obtained with **2a** and the parent catalyst $[Rh_2\{(R)\text{-bnp}\}_4]$ (**26**) in C_6H_6 at 25 °C (−8% *ee*, 70% yield).

Workers at Schering AG-Berlin have developed the synthesis of bis-steroidal binaphthols, which when incorporated into catalysts can lead to interesting, and in some cases increased, enantioselectivity relative to the analogous binaphthol-derived catalysts in certain asymmetric transformations.[47] Construction of a Rh^{II}–phosphate catalyst derived from a ligand such as **37** (Scheme 8) would result in a complex with a more substantial steric wall surrounding the axial binding site at the metal. This appeared attractive in terms of the potential for modifying enantiocontrol. Furthermore, it was considered that the alicyclic component should enhance the solubility in hexane of such a Rh^{II} catalyst, relative to catalyst **26**. Thus, bis-isoequilenine scaffolds **34** and **37** (prepared from estrone)[47d] were converted to the novel catalysts $[Rh_2\{(R,S)\text{-biep}\}_4]$ (**36**; biep = bisisoequileninephosphate) and $[Rh_2\{(S,S)\text{-biep}\}_4]$ (**39**), respectively (Scheme 8, note that the first stereochemical descriptor refers to the axial configuration and the second to that of the methyl-substituted stereogenic centres).

In CH_2Cl_2, both **36** and **39** provide asymmetric induction inferior to **26** and **33** (Table 2, entries 14 and 17 compared with 2 and 10). In hexane, the effectiveness of the bis-steroidal catalysts lie between those of **26** and **33** (entries 15,16 and 18,19 compared with 1 and 11,12). In this solvent, there was a noticeable difference in catalytic activity between the two bis-steroidal catalysts (with **36** reaction was complete within 30 minutes at room temperature, whereas **39** requires it 40 to 50 minutes; this compares with **33** requiring 30 minutes at the same temperature). This may be due to a slight difference in solubility in hexane between the two diastereomers. Catalyst **39** gives slightly higher asymmetric induction than **36** (entries 17–19 and 14–16). Therefore, as found in other asymmetric tranformations with this ligand class, the enantio-



Scheme 8. Synthesis of biep catalysts **36** and **39**. Reagents and conditions: a) $POCl_3$, pyridine, 25 °C, 1 h, then H_2O, 25 °C 15 min, then HCl; b) $[Rh_2(OAc)_4]$, PhCl, reflux, 5 h.

selectivity depends both on the axial chirality and the stereogenic centres in the ligand backbone.[47, 48] Also, as in most (but not all)[47c] previous studies of these ligands, the predominant sense of asymmetric induction observed in our work is determined by the element of axial chirality and not by the stereogenic centres in the ligand structure.

Because the catalyst-free carbonyl ylides in our studies and the studies by Doyle,[32] Ibata[33] and Hashimoto[34] would be achiral, the observation of enantioselectivity provides unambiguous evidence (assuming no catalyst–dipolarophile interaction) for an enantioselective ylide transformation taking place via a catalyst-complexed ylide intermediate **40/41** or dipolar complex **42/43** (for a generalised analysis of the process see Scheme 9).

In this mechanistic analysis, attack of the metal carbene complex by the carbonyl group would give initially a catalyst-complexed ylide species **40/41**, in which the catalyst is attached to the originally carbenic carbon. A recent computational study by Padwa and co-workers indicates that a catalyst-complexed carbonyl ylide can be of lower energy

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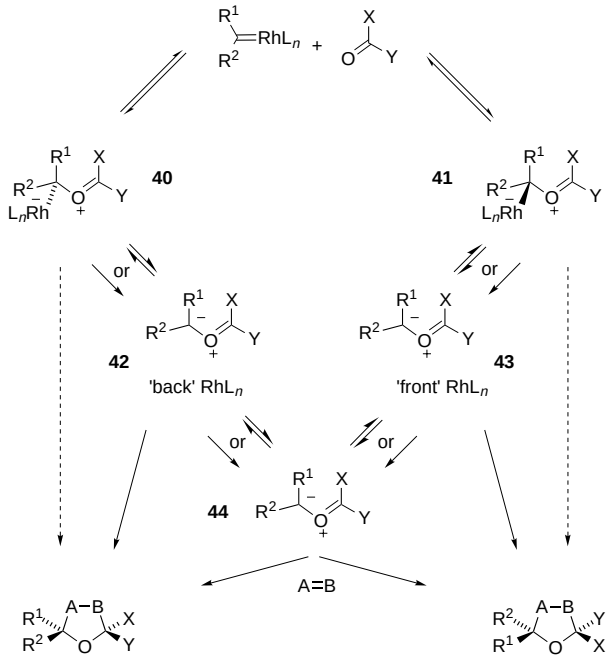

Scheme 9. Mechanistic analysis.

than its acyclic metal–carbene complex precursor, and can also be lower in energy than a free carbonyl ylide and catalyst ([$Rh_2(O_2CH)_4$] was used in the calculations).[49] Assuming that during the ensuing cycloaddition the catalyst remains associated with the C=O$^+$–C$^-$ part of the ylide, rather than ligation with a carbonyl group or carbonyl groups, then the chiral catalyst can only be associated with either face of a single carbonyl ylide, since (with the exception of Doyles studies)[32] the ylide is part of a ring. Cycloaddition could then occur on the opposite face of the ylide to the catalyst as the catalyst dissociates. In the case of substrate **2** the cycloaddition is likely to be a concerted process from dipolar complex **42/43**, because the dipolarophile is a simple unpolarised alkene (the situation could be different with DMAD). If one also assumes for the moment that no cycloaddition occurs competitively from the catalyst-free ylide **44**, then two suggestions for the origin of the enantioselectivity are as follows. If the two catalyst-associated ylide isomers do not interconvert within the timescale of the cycloaddition, then the enantioselectivity is governed by the preference of the tethered carbonyl to cyclise to the *Re* or *Si* face of the metal–carbene complex under the influence of the chiral ligands of the catalyst. Alternatively, interconversion between the two catalyst-associated ylide isomers through a dissociation/recombination mechanism (dissociation to the acyclic metal–carbene complex) could be faster than the rate(s) of cycloaddition. This last case describes a Curtin–Hammett situation with the relative proportions of the two catalyst-associated ylides being inconsequential and the enantioselectivity being determined by the difference in the free energies of the activation barriers ($\Delta\Delta G^{\neq}$) of the two catalyst-associated ylide isomers for cycloaddition. Regardless of which of these two processes operates, enantioselectivity could be affected if the catalyst dissociates from the ylide prior to, or competitively with, cycloaddition from the catalyst-associated ylide. If catalyst dissociation is reversible and is fast compared with the rates of catalyst-associated and catalyst-free cycloadditions then the relative rates of these cycloadditions will also be an important factor influencing the level of asymmetric induction observed.

Conclusion

In summary, our results indicate that dirhodium tetrakisbinaphtholphosphate catalysts can be superior to the more commonly utilised carboxylates and carboxamidates in asymmetric transformations of diazocarbonyl compounds and deserve to be more fully investigated.[50] More generally our studies provide a significant contribution to the emerging concept that metal-catalysed dipole formation followed by cycloaddition can be a powerful method for asymmetric synthesis. Our work described herein (together with Ibata's and Hashimoto's results) suggests that efficient catalyst control over enantioselectivity (and diastereoselectivity) in carbonyl ylide cycloadditions can eventually be developed, although major challenges clearly lie ahead in developing catalysts that are effective with various ylide types and substitution patterns, and different dipolarophiles.

Experimental Section

General techniques: All reactions requiring anhydrous conditions were conducted in flame-dried apparatus under an atmosphere of argon. Syringes and needles for the transfer of reagents were dried at 140 °C and allowed to cool in a desiccator over P_2O_5 before use. Ethers were distilled from sodium/benzophenone, (chlorinated) hydrocarbons and Et_3N from CaH_2. Reactions were monitored by TLC by using commercially available glass-backed plates, pre-coated with a 0.25 mm layer of silica containing a fluorescent indicator (Merck). Column chromatography was carried out on Kieselgel 60 (40–63 μm). Light petroleum refers to the fraction with b.p. 40–60 °C. [α] values are given in 10^{-1} deg cm^2 g^{-1}. IR spectra were recorded as thin films unless stated otherwise. Peak intensities are specified as strong (s), medium (m) or weak (w). ^{1}H and ^{13}C NMR spectra were recorded in $CDCl_3$ unless stated otherwise with a Bruker AC200, a Varian Gemini 200, a Bruker DPX400, a Bruker AM500 or a Bruker AMX500 spectrometer (C_q = quaternary C atom). Chemical shifts are reported relative to $CHCl_3$ [$\delta_H = 7.26$, δ_C(central line of t) = 77.0]. Mass spectra were obtained by the EPSRC National Mass Spectrometry Service Centre at the University of Swansea by using a Micromass Quattro II low-resolution triple quadrupole mass spectrometer or, for accurate masses, by using a Finnigan MAT 900 XLT high-resolution double-focusing mass spectrometer with tandem ion trap. Chiral stationary phase HPLC was performed by using a Daicel Chiralpak AD column (4.6 mm × 250 mm) on a Gilson system with 712 Controller Software and a 118 UV/VIS detector set at 254 nm. Retention times for major ($t_R$mj) and minor ($t_R$mn) enantiomers are given in minutes. Chiral gas chromatography was carried out using a CE Instruments Trace GC (Thermoquest) machine with CP Chirasil Dex-CD or Cydex-β columns. Retention times for major ($t_R$mj) and minor ($t_R$mn) enantiomers are given in minutes.

4-Oxo-8-nonenoic acid (4):[10] A stirred solution of 2,3-dihydrofuran (11.4 mL, 151 mmol) in THF (650 mL) was cooled to −78 °C before dropwise addition of *t*BuLi (109 mL of a 1.7 M solution in pentane) through a cannula over 1 h. The solution was warmed to 0 °C for 30 min before being recooled to −78 °C. A solution of 5-iodo-1-pentene[51] (29.7 g, 151 mmol) in THF (30 mL) was added dropwise through a dropping funnel, and the resulting solution was warmed to room temperature and then stirred for 1 h. The reaction mixture was recooled to 0 °C and quenched by careful addition of saturated aqueous NH_4Cl solution (100 mL). The

aqueous phase was extracted with pentane/Et_2O (3×150 mL, 1:1 v/v) and the combined organic components were dried ($MgSO_4$) before concentration under reduced pressure until the volume was approximately 500 mL. The solution of alkylated dihydrofuran was stirred and Jones' reagent[52] (122 mL of a 2.7 M aqueous solution) was added dropwise over 90 min. After 18 h the reaction mixture was diluted with Et_2O (300 mL) and H_2O (300 mL), and stirred vigorously for 30 min. The aqueous phase was separated, extracted with Et_2O (4×200 mL) and the combined organic components were washed with H_2O (3×100 mL) and extracted with 10% aqueous NaOH solution (3×200 mL). The combined basic portions were cooled to 0 °C and acidified to pH 1 with HCl (6 N). The cloudy aqueous component was extracted with CH_2Cl_2 (4×200 mL) and the combined organic components dried ($MgSO_4$). Concentration under reduced pressure gave the keto acid **4** as a white solid (17.5 g, 68% over 2 steps). ^{1}H NMR (400 MHz, $CDCl_3$, 25 °C): $\delta = 1.63-1.70$ (m, 2H; CH_2CH$_2$CH=CH$_2$), 2.00–2.06 (m, 2H; CH_2CH=CH$_2$), 2.44 (t, ^3J(H,H) = 7.4 Hz, 2H; CH_2(CH$_2$)$_2$CH=CH$_2$), 2.58–2.70 (m, 4H; C(O)CH$_2$CH$_2$C(O)), 4.86–4.96 (m, 2H; CH=CH$_2$), 5.74 (ddt, ^3J(H,H) = 17.0, 10.0, 7.0 Hz, 1H; CH=CH$_2$), 11.58 (br s, 1H; CO_2H); ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C): $\delta = 22.7, 27.7, 32.9, 36.8, 41.7$ ($5 \times$ CH$_2$), 115.2 (CH=CH$_2$), 137.8 (CH=CH$_2$), 179.0 (CO_2H), 208.8 (C=O); IR (KBr): $\tilde{\nu} = 3100$ (w, br; OH), 2938 (m; CH), 1712 (s; C=O), 1416 (m), 1248 cm^{-1} (m).

***tert*-Butyl 3,6-dioxo-10-undecenoate (5c)**: Carbonyl diimidazole (3.04 g, 18.75 mmol) was added to a stirred solution of keto acid **4** (2.66 g, 15.63 mmol) in THF (30 mL) at 0 °C. After 15 min at 0 °C the ice bath was removed and the reaction mixture was allowed to warm to room temperature for 1 h. In a separate flask, mono-*tert*-butyl malonate (6.00 g, 37.46 mmol) was dissolved in THF (100 mL), cooled to −78 °C and to this was added Bu_2Mg (18.80 mL of a 1.0 M solution in heptane) by syringe. The mixture was stirred for 15 min at −78 °C and then for 1 h at room temperature. The solvent was removed, the residue dissolved in THF (50 mL) and the acyl imidazolide added through a cannula, rinsing the flask with a second portion of THF (10 mL). After 18 h the reaction was quenched by the addition of 10% aqueous citric acid solution (30 mL), the layers separated and the aqueous component extracted with Et_2O ($2 \times$ 60 mL). The combined organic components were washed with saturated aqueous $NaHCO_3$ solution (30 mL) and brine (30 mL), dried ($MgSO_4$) and concentrated under reduced pressure. The crude product mixture was purified by column chromatography (light petroleum/Et_2O 5:1) to give 3,6-diketoester **5c** as a colourless oil (2.41 g, 58%). R_f = 0.35 (light petroleum/Et_2O 1:1); ^{1}H NMR (500 MHz, $CDCl_3$, 25 °C): $\delta = 1.47$ (s, 9H; C(CH$_3$)$_3$), 1.64–1.71 (m, 2H; CH_2CH$_2$CH=CH$_2$), 2.01–2.10 (m, 2H; CH_2CH=CH$_2$), 2.47 (t, ^3J(H,H) = 7.4 Hz, 2H; CH_2(CH$_2$)$_2$CH=CH$_2$), 2.69–2.72, 2.80–2.83 ($2 \times$ m, $2 \times$ 2H; C(O)CH$_2$CH$_2$C(O)), 3.41 (s, 2H; C(O)CH$_2$C(O)), 4.97–5.00 (m, 2H; CH=CH$_2$), 5.76 (ddt, ^3J(H,H) = 16.9, 10.1, 6.7 Hz, 1H; CH=CH$_2$); ^{13}C NMR (125 MHz, $CDCl_3$, 25 °C): $\delta = 27.8$ (C(CH$_3$)$_3$), 22.7, 32.9, 36.0, 36.2, 41.7 ($5 \times$ CH$_2$), 50.5 (C(O)CH$_2$C(O)), 81.8 (C(CH$_3$)$_3$), 115.1 (CH=CH$_2$), 137.8 (CH=CH$_2$), 166.3 (CO_2), 201.9, 208.8 ($2 \times$ C=O); IR: $\tilde{\nu}$ = 2979 (m; CH), 2936 (m; CH), 1769 (s; C=O), 1737 (s; C=O), 1715 (s; C=O), 1410 (m), 1394 (m), 1339 (m), 1321 (m), 1258 (m), 1153 cm^{-1} (m); MS (CI+): *m/z* (%): 286 (38) $[M+NH_4]^+$, 240 (38), 230 (100), 186 (70), 109 (20), 52 (56); HRMS: calcd for $C_{15}H_{28}O_4$: 286.2018; found: 286.2018 $[M+NH_4]^+$.

***tert*-Butyl 2-diazo-3,6-dioxo-10-undecenoate (2c)**: Et_3N (1.34 mL, 9.69 mmol) was added to a stirred solution of 3,6-diketoester **5c** (2.36 g, 8.81 mmol) and 4-acetamidobenzenesulfonyl azide[53] (2.32 g, 9.69 mmol) in MeCN (70 mL). After 15 h the reaction mixture was filtered and the precipitate washed with CH_2Cl_2 (70 mL). Saturated aqueous NH_4Cl (20 mL) solution was added to the combined organics, the layers were separated and the aqueous phase extracted with CH_2Cl_2 (20 mL). The organic components were washed with brine (20 mL), dried ($MgSO_4$) and absorbed onto silica. Purification by column chromatography (light petroleum/Et_2O 10:1) gave cycloaddition precursor **2c** as a yellow oil (2.35 g, 91%). R_f = 0.61 (light petroleum/Et_2O 1:1); ^{1}H NMR (500 MHz, $CDCl_3$, 25 °C): $\delta = 1.53$ (s, 9H; C(CH$_3$)$_3$), 1.67–1.73 (m, 2H; CH_2CH$_2$CH=CH$_2$), 2.07 (app. q, ^3J(H,H) = 7.1 Hz, 2H; CH_2CH=CH$_2$), 2.49 (t, ^3J(H,H) = 7.4 Hz, 2H; CH_2(CH$_2$)$_2$CH=CH$_2$), 2.72–2.74, 3.09–3.12 ($2 \times$ m, $2 \times$ 2H; C(O)CH$_2$CH$_2$C(O)), 4.96–5.04 (m, 2H; CH=CH$_2$), 5.77 (ddt, ^3J(H,H) = 16.7, 10.2, 6.7 Hz, 1H; CH=CH$_2$); ^{13}C NMR (125 MHz, $CDCl_3$, 25 °C): $\delta = 22.7$ (CH$_2$CH$_2$CH=CH$_2$), 28.2 (C(CH$_3$)$_3$), 29.6, 33.0, 34.2, 36.1 ($4 \times$ CH$_2$), 68.0 (CN$_2$), 83.1 (C(CH$_3$)$_3$), 115.1 (CH=CH$_2$), 137.9 (CH=CH$_2$), 160.5 (CO_2), 191.5, 209.0 ($2 \times$ C=O); IR: $\tilde{\nu}$ = 2969 (m; CH), 2929 (s; CH), 2850 (w; CH), 2132 (s; CN$_2$), 1716 (s; C=O), 1652 (s), 1369 (s), 1312 (s), 1133 cm^{-1} (s); MS (CI+): *m/z* (%): 312 (37) $[M+NH_4]^+$, 295 (70) $[M+H]^+$, 286 (37), 284 (35), 256 (100), 239 (48), 230 (31); HRMS: calcd for $C_{15}H_{23}N_2O_4$: 295.1657; found: 295.1658 $[M+H]^+$.

7-Carbo-*tert*-butoxy-11-oxa-tricyclo[5.3.1.0^{1,5}]undecan-8-one (3c): A Rh^{II} catalyst (0.2–1.0 mol%) was added to a stirred solution of cycloaddition precursor **2c** (approx. 70 mg, 0.24 mmol) in degassed[54] solvent (7 mL) at the desired temperature. When TLC analysis indicated complete consumption of starting material (0.3 h–3 h) the solution was concentrated under reduced pressure and the crude product mixture purified by column chromatography (light petroleum/Et_2O 8:2) to give the cycloadduct **3c** as a colourless oil. R_f = 0.37 (light petroleum/Et_2O 1:1); $[\alpha]_D^{20} = +12.1$ (c = 1.0 in $CHCl_3$) (Table 2, entry 13); ^{1}H NMR (500 MHz, $CDCl_3$, 25 °C): $\delta = 1.50$ (s, 9H; C(CH$_3$)$_3$), 1.50–1.57 (m, 2H; OCCH$_a$H$_b$CH$_2$CH$_2$CH, OCCH$_2$CH-CH$_a$H$_b$CH$_2$CH$_2$), 1.67–1.72 (m, 1H; OCCH$_2$CH$_a$H$_b$CH$_2$CH), 1.83–2.02 (m, 4H; OCCH$_2$CH$_a$H$_b$CH$_2$CH, OCCH$_2$CHCH$_a$H$_b$, C(O)CH$_a$H$_b$, OC-CH$_a$H$_b$CH), 2.10–2.18 (m, 1H; OCCH$_a$H$_b$CH$_2$CH$_2$CH), 2.44 (app. dt, ^2J(H,H) = 12.9 Hz, ^3J(H,H) = 8.5 Hz, 1H; C(O)CH$_2$CH$_a$H$_b$), 2.47–2.59 (m, 4H; CHCH$_a$H$_b$CC(O)CH$_a$H$_b$CH$_a$H$_b$C); ^{13}C NMR (50 MHz, $CDCl_3$, 25 °C): $\delta = 27.9$ (C(CH$_3$)$_3$), 25.1, 33.6, 34.0, 34.3, 36.7, 41.7 ($6 \times$ CH$_2$), 45.1 (CH), 82.5 (C(CH$_3$)$_3$), 91.5, 93.8 ($2 \times$ C$_q$), 167.1 (CO_2), 205.2 (C=O); IR: $\tilde{\nu}$ = 2956 (m; CH), 1744 (s; C=O), 1724 (s; C=O), 1369 (m), 1320 (m), 1151 (m), 1137 (m), 1066 cm^{-1} (m); MS (EI+): *m/z* (%): 266 (3) $[M]^+$, 210 (13), 182 (16), 164 (22), 137 (33), 94 (50), 79 (47), 57 (100); HRMS: calcd for $C_{15}H_{22}O_4$: 266.1518; found: 266.1518 $[M]^+$.

GC analysis of 3c for *ee* determination: (CP Chirasil Dex-CD, 140 °C isotherm, 0.5 mL min^{-1}, 2 mg mL^{-1}), $t_R$mj = 32.4 min; $t_R$mn = 34.8 min.

Transesterification of 3c to 3a for *ee* determination: A solution of cycloadduct **3c** (10–60 mg) in CH_2Cl_2/TFA (10 mL, 9:1 v/v) was stirred at room temperature for 1 h. The reaction mixture was concentrated under reduced pressure to yield the cycloadduct carboxylic acid as a white solid (quant.). *para*-Toluenesulfonic acid (*p*-TSA, approx. 10 mg, 0.05 mmol) was added to a solution of the acid in MeOH (10 mL) and the solution was heated at reflux for 18 h. The reaction mixture was absorbed onto silica and purified by column chromatography (light petroleum/Et_2O 3:1) to give the methyl ester **3a** as a white solid (approx. 85% over 2 steps).

Derivatisation as benzyl oxime ether for *ee* determination: *O*-Benzylhydroxylamine hydrochloride (219 mg, 1.37 mmol) was added to a stirred solution of methyl ester **3a** (205 mg, 0.92 mmol) and NaOAc (113 mg, 1.37 mmol) in MeOH (5 mL). After 1 h the reaction mixture was absorbed onto silica and purified by column chromatography (light petroleum/Et_2O 10:1) to give the *trans* benzyl oxime ether as a colourless viscous oil (263 mg, 87%). HPLC analysis: (hexane/EtOH 90:10, 0.5 mL min^{-1}, 2 mg mL^{-1}), $t_R$mj = 11.2 min; $t_R$mn = 14.0 min (derived from (+)-**3c**).

Tetrakis[(1*S*,3*S*,5*S*)-2-(4-dodecylbenzenesulfonyl)-2-azabicyclo[3.3.0]octan-3-carboxylato]dirhodium (16): A solution of 4-(*n*-dodecyl)benzenesulfonyl chloride (780 mg, 2.26 mmol, single isomer) in THF (5 mL) was added to a stirred solution of (1*S*,3*S*,5*S*)-2-azabicyclo[3.3.0]octane-3-carboxylic acid hydrochloride salt[55] (334 mg, 1.74 mmol) and Na_2CO_3 (740 mg, 6.98 mmol) in H_2O (10 mL). After 15 h the reaction mixture was diluted with H_2O (100 mL) and Et_2O (30 mL), the aqueous phase was then separated and acidified to pH 1 with conc. HCl. The aqueous solution was saturated with NaCl and extracted with EtOAc (5×100 mL). The combined organic components were dried ($MgSO_4$) and concentrated under reduced pressure to yield a crude product mixture which was purified by column chromatography (CH_2Cl_2/MeOH 19:1) to give the *N*-arylsulfonyl acid as a colourless viscous oil (657 mg, 82%) which partially solidifed on storage in the freezer. R_f = 0.37 (CH_2Cl_2/MeOH 9:1); $[\alpha]_D^{20} = -18.1$ (c = 1.0 in $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$, 25 °C): $\delta = 0.87-0.92$ (m, 3H; CH$_3$), 1.22–1.39 (m, 16H), 1.44–1.88 (m, 9H), 1.95–2.16 (m, 3H), 2.49–2.51 (m, 1H), 2.69 (t, ^3J(H,H) = 7.8 Hz, 2H), 4.02–4.10 (m, 1H; CHN), 4.15–4.24 (m, 1H; CHCO$_2$H), 7.36 (m, 2H; C(Ar, 3/5)H), 7.80 (m, 2H; C(Ar, 2/6)H); ^{13}C NMR (125 MHz, $CDCl_3$, 25 °C): $\delta = 14.0$ (CH$_3$), 22.6, 24.3, 29.2, 29.3, 29.4, 29.5, 29.6, 30.9, 31.3, 31.8, 34.3, 35.2 and 35.8 ($15 \times$ CH$_2$), 43.0 (CH), 63.5 (br, CHN), 67.1 (CHCO$_2$H), 127.9, 129.0 ($2 \times$ C(Ar)H), 133.9 and 148.8 ($2 \times$ C$_q$(Ar)), 178.0 (br, CO_2H); IR: $\tilde{\nu}$ = 2926 (s; CH), 2955 (m; CH), 1727 (m; C=O), 1351 (m), 1162 cm^{-1} (m); MS (APCI−): *m/z* (%): 463 (23), 462 (100) $[M-H]^+$, 460 (28), 309 (18), 125 (12); HRMS: calcd for $C_{26}H_{42}NO_4S$: 464.2834; found: 464.2834 $[M+H]^+$.

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$[Rh_2(OAc)_4]$ (32 mg, 0.07 mmol) was added to a stirred solution of the *N*-arylsulfonyl acid (199 mg, 0.43 mmol) in chlorobenzene (50 mL). The solution was heated under reflux in an apparatus fitted with a soxhlet extractor containing a thimble of $CaCO_3$ for 6 days, the thimble being replaced every 2 days. The mixture was concentrated under reduced pressure and the residue dissolved in CH_2Cl_2 (20 mL). The solution was then washed with saturated aqueous $NaHCO_3$ solution (10 mL), dried (Na_2SO_4) and concentrated under reduced pressure. The crude product was purified by column chromatography (light petroleum/Et_2O 2:1 → Et_2O) to give catalyst **16** as a green solid (32 mg, 23%). An analytical sample of the bis-H_2O adduct was prepared by heating (100 °C) under vacuum (0.1 mmHg) for 18 h, after which the sample picked up H_2O from the laboratory atmosphere. M.p. 160–162 °C; $[\alpha]_D^{20} = -129.0$ ($c = 0.04$ in $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$, 25 °C): $\delta = 0.88$ (t, ^3J(H,H) = 6.9 Hz, 12H; 4 × CH_3), 1.22–1.48 (m, 80H), 1.50–1.68 (m, 16H), 1.68–1.85 (m, 12H), 1.98–2.10 (m, 4H), 2.18–2.38 (m, 4H), 2.60–2.70 (m, 8H), 3.80–3.90 (m, 4H; 4 × CHN), 4.08–4.22 (m, 4H; 4 × $CHCO_2$), 7.27 (d, ^3J(H,H) = 8.0 Hz, 8H; 4 × C(Ar, 3/5)H), 7.74 (d, 8H; 4 × C(Ar, 4/6)H); ^{13}C NMR (125 MHz, $CDCl_3$, 25 °C): $\delta = 14.1$ (CH_3), 22.7, 24.1, 29.3, 29.3, 29.4, 29.5, 29.6, 30.6, 31.1, 31.9, 33.3, 35.7, 35.8 (60 × CH_2), 42.6 (CH), 64.6, 66.6 (8 × CHN), 128.0, 128.7 (C(Ar)H), 135.4, 148.0 (C_q(Ar)), 191.9 (CO_2); IR (KBr): $\tilde{\nu} = 2942$ (s; CH), 2854 (m; CH), 1605 (s; CO_2), 1418 (m), 1353 (m), 1164 cm^{-1} (s); MS (FAB+, NOBA matrix): *m/z* (%): 2091 (0.4), 2056 (2.4) $[M+H]^+$, 1781 (0.4), 1746 (6.6), 662 (41), 418 (100); elemental analysis calcd (%) for $C_{104}H_{164}N_4O_{18}S_4Rh_2 \cdot 2H_2O$: C 59.70, H 7.90, N 2.68; found: C 59.15, H 7.36, N 2.68.

Tetrakis[(1*S*,3*R*,4*R*)-2-(4-dodecylbenzenesulfonyl)-2-azabicyclo[2.2.1]-heptane-3-carboxylato]dirhodium (17b): (1*S*,3*R*,4*R*)-2-Azabicyclo[2.2.1]-heptane-3-carboxylic acid[28] (91 mg, 0.64 mmol) and Na_2CO_3 (210 mg, 1.93 mmol) was added to a stirred solution of 4(*n*-dodecyl)benzenesulfonyl chloride (290 mg, 0.84 mmol) in H_2O (5 mL) and THF (2.5 mL). The solution was stirred at room temperature for 3 days before dilution with H_2O (20 mL). The reaction mixture was acidified to pH 1.5 with conc. HCl and carefully saturated with NaCl. The mixture was extracted with CH_2Cl_2 (×3), and the combined organic layers were dried ($MgSO_4$) and concentrated under reduced pressure. The crude residue was purified by column chromatography (light petroleum/Et_2O 1:1) to give the *N*-arylsulfonyl acid as a yellow oil (0.132 g, 46%). $[\alpha]_D^{20} = +68.6$ ($c = 0.7$ in $CHCl_3$); ^{1}H NMR (200 MHz, $CDCl_3$, 25 °C): $\delta = 0.87$ (m, 3H; CH_3), 1.12–2.08 (m, 26H; $ArCH_2(CH_2)_{10}CH_3$, $NCHCH_2CH_2CH_2CHCHCOOH$), 2.60–2.75 (m, 2H; $ArCH_2$), 2.82 (br s, 1H), 3.93 (br s, 1H), 4.11 (br s, 1H), 7.31 (d, ^3J(H,H) = 7.6 Hz, 2H), 7.84 (d, ^3J(H,H) = 7.6 Hz, 2H), 9.04 (br s, 1H, COOH); ^{13}C NMR (50 MHz, $CDCl_3$, 25 °C): $\delta = 13.9$ (CH_3), 22.4, 27.4, 28.4, 28.9–29.4, 30.8, 31.7 (12 × CH_2), 35.6 (CH), 36.2, 43.2 (2 × CH_2), 60.0, 64.4 (2 × CH), 127.8, 129.0 (4 × C(Ar)H), 137.0, 148.8 (2 × C_q(Ar)), 175.7 (COOH); IR: $\tilde{\nu} = 3270$ (s; OH), 2923 (s; CH), 2854 (s; CH), 1725 (m; C=O), 1597 (w; arC=C), 1466 (w), 1340 (m), 1155 cm^{-1} (m); MS (CI+): *m/z* (%): 467 (50) $[M+NH_4]^+$, 450 (31) $[M+H]^+$, 420 (2), 404 (9), 364 (9), 362 (23), 294 (15), 278 (30), 246 (25), 142 (3), 113 (3), 96 (100); HRMS: calcd for $C_{25}H_{43}SN_2O_4$: 467.2944; found: 467.2948 $[M+NH_4]^+$.

A stirred solution of the *N*-arylsulfonyl acid (0.499 g, 1.11 mmol) and $Na_4Rh_2(CO_3)_4$[56] (75 mg, 0.14 mmol) in H_2O (7.5 mL) was heated at 90 °C for 1 h, during which time the colour changed from blue to green. The reaction mixture was cooled and the solvent evaporated under reduced pressure. The residue was purified by column chromatography (EtOAc) to give the catalyst **17b** as a green powder (0.121 g, 43%). M.p. 113 °C; $[\alpha]_D^{20} = +175.0$ ($c = 0.6$ in $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$, 25 °C): $\delta = 0.87$–0.90 (m, 12H; 4 × CH_3), 0.90–1.87 (m, 104H; 4 × $ArCH_2(CH_2)_{10}CH_3$, 4 × $NCHCH_2CH_2CH_2CHCHCOOH$), 2.66–2.76 (m, 12H; 4 × $CHCHCOO$, 4 × $ArCH_2$), 3.73 (br s, 4H), 3.93 (br s, 4H), 7.32 (d, ^3J(H,H) = 7.8 Hz, 8H), 7.83 (d, ^3J(H,H) = 7.8 Hz, 8H); ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C): $\delta = 14.6$ (4 × CH_3), 23.2, 29.6–30.2–30.3, 31.7, 32.4 (48 × CH_2), 36.4 (4 × CH), 37.4, 44.4 (8 × CH_2), 59.6, 66.7 (8 × CH), 128.3, 129.3 (16 × C(Ar)H), 138.5, 148.4 (8 × C_q(Ar)), 191.5 (COO); IR (KBr): $\tilde{\nu} = 2924$ (s; CH), 2853 (m; CH), 1601 (m), 1460 (w), 1328 (m), 1156 cm^{-1} (m); MS (FAB+, NOBA matrix): *m/z* (%): 2023 (32) $[M+Na]^+$, 2000 (55) $[M]^+$, 1691 (35), 1098 (31), 648 (36), 404 (100).

Tetrakis[(*R*)-6,6′-dibromo-1,1′-binaphthyl-2,2′-diylphosphate]dirhodium (28): A round-bottomed flask (25 mL) fitted with a short path distillation unit was charged with a solution of (*R*)-6,6′-dibromobinaphtholphosphoric acid[42] (191 mg, 0.38 mmol) in PhCl (10 mL). $[Rh_2(OAc)_4]$ (28 mg, 63 μmol) was added and the solution was heated at reflux. The solvent was distilled from the reaction mixture at a rate of approximately 8 mL h^{-1}, further portions of PhCl (6 mL) were added when an equal volume had been removed. After 5 h the reaction mixture was concentrated under reduced pressure and the residue was purified by column chromatography (CH_2Cl_2) to give the catalyst **28** as a green solid (144 mg, 100%). The catalyst could be further purified by recrystallisation from THF/MeOH. An analytical sample of the bis-H_2O adduct was prepared by heating (100 °C) under vacuum (0.1 mmHg) for 18 h, after which the sample picked up H_2O from the laboratory atmosphere. M.p. >300 °C (THF/MeOH); $[\alpha]_D^{20} = +20.0$ ($c = 0.05$ in $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$, 25 °C): $\delta = 7.26$ (d, ^3J(H,H) = 9.1 Hz, 8H; 8 × OCCCCH), 7.41 (dd, ^3J(H,H) = 9.1 Hz, ^4J(H,H) = 1.7 Hz, 8H; 8 × OCCCCHC*H*CBr), 7.56 (d, ^3J(H,H) = 8.9 Hz, 8H; 8 × OCCH), 7.77 (d, ^3J(H,H) = 8.9 Hz, 8H; 8 × OCCHC*H*CCHCBr), 8.06 (d, ^4J(H,H) = 1.7 Hz, 8H; 2 × BrCCHC); ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C): $\delta = 119.8$, 121.4 (16 × C_q), 122.2, 128.5, 130.1, 130.5, 130.5 (40 × CH), 130.7, 132.9, 147.8 (24 × C_q); IR (KBr): $\tilde{\nu} = 1585$ (w), 1493 (w), 1324 (w), 1236 (w), 1061 cm^{-1} (s); MS (FAB+, NOBA): *m/z* (%): 2226 (100) $[M+H]^+$ (4 × ^{79}Br and 4 × ^{81}Br), 1720 (42), 1215 (32), 1084 (35), data not available below *m/z* 800; elemental analysis calcd (%) for $C_{80}H_{40}Br_8O_{16}P_4Rh_2 \cdot 2H_2O$: C 42.48, H 1.96; found: C 42.43, H 2.05.

Tetrakis[(*R*)-6,6′-didodecyl-1,1′-binaphthyl-2,2′-diylphosphate]dirhodium [Rh_2{(*R*)-ddbnp}$_4$] (33): [1,3-Bis(diphenylphosphino)propane]$NiCl_2$ (1 mg, 2 μmol) and *n*-dodecyl magnesium bromide (0.48 mL of a 1.0 M solution in Et_2O, 0.48 mmol, Aldrich) was added to a stirred solution of (*R*)-2,2′-dibenzyloxy-6,6′-dibromo-1,1′-binaphthyl (**29**)[43] (100 mg, 0.16 mmol) in Et_2O (5 mL). After heating under reflux for 18 h the solution was cooled to room temperature. H_2O (5 mL) was carefully added followed by HCl (2 M, 5 mL); the aqueous phase was then separated and extracted with EtOAc (3 × 10 mL). The combined organic components were washed with brine (10 mL), dried ($MgSO_4$) and concentrated under reduced pressure. The crude product mixture was purified by column chromatography (1.5% Et_2O in light petroleum) to give didodecylbisether **30** as a colourless viscous oil (96 mg, 75%). $R_f = 0.63$ (light petroleum/Et_2O 2:1); $[\alpha]_D^{20} = +205.7$ ($c = 1.0$ in $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$, 25 °C): $\delta = 0.90$ (t, ^3J(H,H) = 6.8 Hz, 6H; 2 × CH_3), 1.22–1.41 (m, 36H; 2 × $(CH_2)_9CH_3$), 1.65–1.72 (m, 4H; 2 × $ArCH_2CH_2$), 2.73 (t, ^3J(H,H) = 7.7 Hz, 4H; 2 × $ArCH_2$), 5.04 (s, 4H; 2 × OCH_2), 6.96–6.98 (m, 4H; 2 × OCCCCH, 2 × C(Ar, benzyl)*H*), 7.08–7.18 (m, 10H; 2 × OCCCHC*H*, 8 × C(Ar, benzyl)*H*), 7.39 (d, ^3J(H,H) = 9 Hz, 2H; 2 × OCCH), 7.66 (br s, 2H; 2 × OCCHCHCC*H*), 7.87 (d, ^3J(H,H) = 9 Hz, 2H; 2 × OCCHC*H*); ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C): $\delta = 14.1$ (2 × CH_3), 22.7, 29.4, 20.4, 4 × 29.6, 29.7, 31.4, 31.9, 35.9 (22 × CH_2), 71.3 (2 × OCH_2), 116.2 (2 × CH), 120.9 (2 × C_q), 125.5, 126.2, 126.8, 127.2, 127.9, 128.1, 128.6 (18 × CH), 129.6, 132.6, 137.7, 138.2, 153.5 (10 × C_q); IR: $\tilde{\nu} = 2924$ (s; CH), 2853 (m; CH), 1596 (w), 1453 (w), 1272 cm^{-1} (w); MS (EI+): *m/z* (%): 803 (5) $[M+H]^+$, 713 (5), 622 (4), 283 (8), 93 (8), 92 (100), 58 (8), 44 (14); HRMS: calcd for $C_{58}H_{74}O_2$: 802.5688; found: 802.5689 $[M]^+$.

NaI (2.13 g, 14.21 mmol) and TMSCl (1.80 mL, 14.21 mmol) was added to a stirred solution of didodecylbisether **30** (1.14g, 1.42 mmol) in $PhCH_3$ (20 mL) and MeCN (40 mL). The reaction mixture was heated at 40 °C for 2 h. After cooling to room temperature, H_2O (40 mL) was added, the aqueous phase was then separated and extracted with Et_2O (3 × 40 mL). The combined organic components were washed with aqueous $Na_2S_2O_3$ solution (1 M, 60 mL) and brine (60 mL), dried ($MgSO_4$) and concentrated under reduced pressure. The crude product mixture was purified by column chromatography (light petroleum/Et_2O 10:1) to give diol **31** as a colourless oil (784 mg, 89%) which solidified on standing. A portion of this product was further purified by crystallisation from MeCN (deposited as an oil which then solidifed) to give essentially enantiomerically pure diol **31** (as determined by HPLC, see below); concentration of the supernatant gave diol **31** of 92% *ee*. $R_f = 0.16$ (light petroleum/Et_2O 3:1); m.p. 67–68 °C (MeCN); $[\alpha]_D^{20} = -51.4$ ($c = 1.0$ in $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$, 25 °C): $\delta = 0.89$ (t, ^3J(H,H) = 6.8 Hz, 6H; 2 × CH_3), 1.22–1.41 (m, 36H; 2 × $(CH_2)_9CH_3$), 1.64–1.71 (m, 4H; 2 × $ArCH_2CH_2$), 2.73 (t, ^3J(H,H) = 7.7 Hz, 4H; 2 × $ArCH_2$), 5.00 (s, 2H; 2 × OH), 7.10 (d, ^3J(H,H) = 8.6 Hz, 2H; 2 × $C_{12}H_{25}CCHCH$), 7.17 (dd, ^3J(H,H) = 8.6 Hz, ^4J(H,H) = 1.5 Hz, 2H; 2 × $C_{12}H_{25}CCHCH$), 7.35 (d, ^3J(H,H) = 8.9 Hz, 2H; 2 × HOCC*H*), 7.67 (br s, 2H; 2 × $C_{12}H_{25}CCHC$), 7.91 (d, ^3J(H,H) = 8.9 Hz, 2H; HOCCHC*H*); ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C): $\delta = 14.1$ (2 × CH_3), 22.7, 29.3, 29.4, 29.5, 29.6, 29.6, 29.6, 29.7, 31.4, 31.9, 35.8 (22 × CH_2), 110.8 (2 × C_q), 117.6,

124.1, 126.8, 129.0 (8 × CH), 129.6 (2 × C_q), 130.8 (2 × CH), 131.7, 138.6, 152.0 (6 × C_q); IR (KBr): $\tilde{\nu}$ = 3431 (m, br; OH), 2920 (s; CH), 2850 (s; CH), 1601 (m), 1218 (w), 1174 (m), 1145 cm^{-1} (m); MS (APCI −): *m/z* (%): 622 (39), 621 (100) $[M-H]^+$; elemental analysis calcd (%) for $C_{44}H_{62}O_2$: C 84.83, H 10.03; found: C 84.60, H 10.27; HPLC analysis: (hexane/EtOH 70:30, 0.5 mL min^{-1}, 0.1 mg mL^{-1}), $t_R$mj = 7.8 min and $t_R$mn = 9.5 min.

$POCl_3$ (121 μL, 1.30 mmol) was added to a stirred solution of diol **31** (402 mg, 0.65 mmol) in pyridine (3 mL) at room temperature. After 2 h, H_2O (65 μL) and $NaHCO_3$ solution (300 μL) were added in that order, followed by dropwise addition (due to effervescence) of 5% aqueous $NaHCO_3$ solution (6.5 mL). The reaction mixture was partitioned between HCl (2 M, 50 mL) and EtOAc (50 mL), the aqueous phase was then separated and further extracted with EtOAc (2 × 40 mL). The combined organic layers were washed with brine (30 mL), dried ($MgSO_4$) and concentrated under reduced pressure to give acid **32** as a viscous colourless oil (394 mg, 89%) that required no further purification. $[\alpha]_D^{20} = -266.2$ (*c* = 0.7 in $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$, 25 °C): δ = 0.89 (t, ^3J(H,H) = 6.8 Hz, 6H; 2 × CH_3), 1.21–1.49 (m, 36H; 2 × $(CH_2)_9CH_3$), 1.60–1.80 (m, 4H; 2 × $ArCH_2CH_2$), 2.74–2.78 (m, 4H; 2 × $ArCH_2$), 7.16 (d, ^3J(H,H) = 8.5 Hz, 2H; 2 × $C_{12}H_{25}CCHCH$), 7.33 (d, ^3J(H,H) = 8.5 Hz, 2H; 2 × $C_{12}H_{25}CCHCH$), 7.50 (d, ^3J(H,H) = 8.5 Hz, 2H; 2 × OCCH), 7.69 (s, 2H; 2 × $C_{12}H_{25}CCHC$H), 7.86 (d, ^3J(H,H) = 8.5 Hz, 2H; 2 × $OCCHCH$); ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C): δ = 14.1 (2 × CH_3), 22.7, 29.4, 29.4, 29.5, 29.6, 29.6, 29.7, 29.7, 31.2, 31.9, 35.8 (22 × CH_2), 120.5 (2 × CH), 121.4 (2 × C_q), 126.7, 127.0, 128.2, 130.6 (8 × CH), 130.6, 132.0, 140.3, 146.3 (8 × C_q); IR: $\tilde{\nu}$ = 2924 (s; CH), 2853 (m; CH), 1466 (w), 1226 (w), 1028 cm^{-1} (m); MS (CI +): *m/z* (%): 704 (25), 703 (45), 702 (100) $[M+NH_4]^+$, 685 (22) $[M+H]^+$; HRMS: calcd for $C_{44}H_{61}O_4P$: 684.4307; found: 684.4303 $[M]^+$.

A round-bottomed flask (25 mL, B14) fitted with a short path distillation unit was charged with a solution of acid **32** (360 mg, 0.53 mmol) in PhCl (8 mL). $[Rh_2(OAc)_4]$ (39 mg, 0.09 mmol) was added and the solution heated under reflux. The solvent was distilled from the reaction mixture at a rate of approximately 7 mL h^{-1}; further portions of PhCl (6 mL) were added when an equal volume had been removed. After 5 h the reaction mixture was concentrated under reduced pressure and the residue was purified by column chromatography (light petroleum/Et_2O 30:1 → 10:1) to give **33** as a green solid (237 mg, 92%). The product was further purifed by deposition from hot THF (ca. 1 mL) on addition of MeOH (ca. 2 mL). After cooling, the supernatant was removed by pipette, the residue washed with MeOH (3 mL) and dried under vacuum. This was repeated to give the catalyst **33** as a green foam (182 mg, 69%). An analytical sample of the bis-H_2O adduct was prepared by heating (100 °C) under vacuum (0.1 mmHg) for 18 h, after which the sample picked up H_2O from the laboratory atmosphere. M.p. 220–224 °C; $[\alpha]_D^{20} = +60.9$ (*c* = 0.03 in $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$, 25 °C): δ = 0.89 (t, ^3J(H,H) = 6.7 Hz, 24H; 8 × CH_3), 1.21–1.34 (m, 144H; 8 × $(CH_2)_9CH_3$), 1.68–1.71 (m, 16H; 8 × $ArCH_2CH_2$), 2.75 (t, ^3J(H,H) = 7.5 Hz, 16H; 8 × $ArCH_2$), 7.18 (d, ^3J(H,H) = 8.7 Hz, 8H; 8 × $C_{12}H_{25}CCHCH$), 7.43 (d, ^3J(H,H) = 8.7 Hz, 8H; 8 × $C_{12}H_{25}CCHCH$), 7.56 (d, ^3J(H,H) = 8.9 Hz, 8H; 8 × OCCH), 7.65 (s, 8H; 8 × $C_{12}H_{25}CCHC$H), 7.77 (d, ^3J(H,H) = 8.9 Hz, 8H; 8 × $OCCHCH$); ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C): δ = 14.1 (8 × CH_3), 22.7, 29.4, 29.4, 29.5, 29.6, 29.6, 29.7, 29.7, 31.2, 31.9, 35.8 (88 × CH_2), 121.2 (8 × CH), 121.6 (8 × C_q), 126.7, 127.1, 128.0, 130.4 (32 × CH), 130.7, 132.0, 139.9, 147.2 (32 × C_q); IR (KBr): $\tilde{\nu}$ = 2924 (s; CH), 2853 (m; CH), 1591 (w), 1468 (m), 1233 (m), 1205 (m), 1061 cm^{-1} (s); elemental analysis calcd (%) for $C_{176}H_{240}O_{16}P_4Rh_2 \cdot 2H_2O$: C 71.00, H 8.26; found: C 71.21, H 8.16.

Tetrakis[(*R*,*S*)-4,4′-bis(estra-1,3,5(10),6,8-pentaene)-3,3′-diylphosphate]-dirhodium [Rh_2{(*R*,*S*)-biep}$_4$] (36): $POCl_3$ (0.113 mL, 1.21 mmol) was added to a stirred solution of (*R*,*S*)-*bis*-steroid **34**[47d] (0.300 g, 0.60 mmol) in pyridine (2 mL) at room temperature. After 1 h, H_2O (0.25 mL) was added. After 15 minutes, HCl (6 N, 3 mL) was added to the residue. After a further 15 minutes, the precipitate was isolated by filtration and washed with H_2O. Traces of pyridine were removed by dissolving the powder in CH_2Cl_2 and washing with Hcl (2 M). The organic layer was then dried ($MgSO_4$), and evaporated under reduced pressure to give acid **35** as a gold solid (336 mg, 100%). M.p. >340 °C; $[\alpha]_D^{20} = -357.1$ (*c* = 0.28 in $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$, 25 °C): δ = 1.05 (s, 6H; 2 × CH_3), 1.63–1.93 (m, 14H; 2 × $ArCH_2CH_2$, 2 × $ArCHCH_aH_b$, 2 × $ArCHCH_2CH_2$, 2 × $ArCHCH_2CH_2CH_2$), 2.26–2.32 (m, 2H; 2 × $ArCHCH_aH_b$), 2.68–2.70 (m, 2H; 2 × ArCH), 3.05–3.26 (m, 4H; 2 × $ArCH_2$), 6.39 (br s, 2H, 2 × ArOH), 7.05 (d, ^3J(H,H) = 8.7 Hz, 2H), 7.23 (d, ^3J(H,H) = 8.7 Hz, 2H), 7.57 (d, ^3J(H,H) = 8.7 Hz, 2H), 8.17 (d, ^3J(H,H) = 9.1 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C): δ = 25.2 (2 × CH_3), 22.8, 23.6, 31.3, 35.4, 40.9 (10 × CH_2), 39.2 (2 × C_q), 50.7 (2 × CH), 119.9 (2 × *C*(Ar)H), 122.1 (2 × C_q(Ar)), 125.1, 126.2, 129.6 (6 × *C*(Ar)H), 130.1, 130.7, 131.2, 137.2, 146.3 (10 × C_q(Ar)); IR (KBr): $\tilde{\nu}$ = 3392 (w, br; OH), 2923 (s; CH), 2864 (m; CH), 1580 (w; arCC), 1505 (w; ArCC), 1473 (w), 1431 (w), 1387 (w), 1235 (s), 1027 cm^{-1} (s); MS (FAB +, NOBA matrix): *m/z* (%): 587 (100) $[M+Na]^+$, 564 (68) $[M]^+$, 309 (7), 291 (12), 152 (41), 135 (36); HRMS: calcd for $C_{36}H_{41}NO_4P$: 582.2773; found: 582.2773 $[M+NH_4]^+$.

A round-bottomed flask (25 mL) fitted with a short path distillation unit was charged with a solution of acid **35** (0.6 g, 1.06 mmol) in PhCl (15 mL). $[Rh_2(OAc)_4]$ (78 mg, 0.18 mmol) was added and the solution was heated to reflux. The solvent was slowly distilled from the reaction mixture and further portions of PhCl (~6 mL) were added when an equal volume had been removed. After 5 h, the reaction mixture was concentrated under reduced pressure and the residue was purified by column chromatography (light petroleum/CH_2Cl_2 6:5 → CH_2Cl_2) to give a green solid, which was suspended in MeOH (5 mL), filtered and air dried to give the catalyst **36** as a green powder (0.23 g, 53%). M.p. 314 °C; $[\alpha]_D^{20} = +118.3$ (*c* = 0.6 in $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$, 25 °C): δ = 1.05 (s, 24H; 8 × CH_3), 1.59–1.85 (m, 56H; 8 × $ArCH_2CH_2$, 8 × $ArCHCH_aH_b$, 8 × $ArCHCH_2CH_2$, 8 × $ArCHCH_2CH_2CH_2$), 2.27–2.29 (m, 8H; 8 × $ArCHCH_aH_b$), 2.64–2.68 (m, 8H; 8 × ArCH), 2.97–3.11 (m, 16H; 8 × $ArCH_2$), 7.02 (d, ^3J(H,H) = 9.0 Hz, 8H), 7.28 (d, ^3J(H,H) = 9.6 Hz, 8H), 7.54 (d, ^3J(H,H) = 9.0 Hz, 8H), 7.96 (d, ^3J(H,H) = 9.2 Hz, 8H); ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C): δ = 25.3 (8 × CH_3), 22.8, 23.5, 31.3, 35.4 and 40.9 (40 × CH_2), 39.2 (8 × C_q), 50.7 (8 × CH), 120.8 (8 × *C*(Ar)H), 122.3 (8 × C_q(Ar)), 125.3, 125.9, 129.3 (24 × *C*(Ar)H), 130.0, 130.6, 131.2, 136.7 147.2 (40 × C_q(Ar)); ^{31}P NMR (200 MHz, $CDCl_3$, 25 °C): δ = 21.5; IR (KBr): $\tilde{\nu}$ = 2949 (m; CH), 2866 (m; CH), 1475 (w), 1458 (w), 1388 cm^{-1} (w); MS (FAB +, NOBA matrix): *m/z* (%): 2460 (17) $[M]^+$, 1896 (43), 1330 (14), 588 (97), 313 (100).

Tetrakis[(*S*,*S*)-4,4′-bis(estra-1,3,5(10),6,8-pentaene)-3,3′-diylphosphate]-dirhodium [Rh_2{(*S*,*S*)-biep}$_4$] (39): $POCl_3$ (0.113 mL, ρ = 1.645, 1.21 mmol) was added to a stirred solution of (*S*,*S*)-*bis*-steroid **37**[47d] (0.300 g, 0.60 mmol) in pyridine (2 mL) at room temperature. After 1 h, H_2O (0.25 mL) was added. After 15 minutes, HCl (6 N, 3 mL) was added to the residue. After a further 15 minutes, the precipitate was isolated by filtration and washed with H_2O. Traces of pyridine were removed by dissolving the powder in CH_2Cl_2 and washing with HCl (2 M). The organic solution was then dried ($MgSO_4$), and the solvent was evaporated under reduced pressure to give acid **38** as a gold solid (317 mg, 94%). M.p. > 340 °C; $[\alpha]_D^{20} = +522.7$ (*c* = 1.5 in $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$, 25 °C): δ = 1.15 (s, 6H; 2 × CH_3), 1.50–1.88 (m, 14H; 2 × $ArCH_2CH_2$, 2 × $ArCHCH_aH_b$, 2 × $ArCHCH_2CH_2$, 2 × $ArCHCH_2CH_2CH_2$), 2.18–2.25 (m, 2H; 2 × $ArCHCH_aH_b$), 2.75–2.79 (t, ^3J(H,H) = 8.8 Hz, 2H; 2 × ArCH), 3.08–3.23 (m, 4H; 2 × $ArCH_2$), 7.07 (d, ^3J(H,H) = 8.8 Hz, 2H), 7.22 (d, ^3J(H,H) = 8.8 Hz, 2H), 7.57 (d, ^3J(H,H) = 9.0 Hz, 2H), 8.18 (d, ^3J(H,H) = 9.2 Hz, 2H), 9.90 (br s, 2H, 2 × ArOH); ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C): δ = 26.0 (2 × CH_3), 22.8, 23.2, 31.6, 35.4, 40.4 (10 × CH_2), 39.3 (2 × C_q), 50.4 (2 × CH), 120.0 (2 × *C*(Ar)H), 122.0 (2 × C_q(Ar)), 125.1, 126.2, 129.3 (6 × *C*(Ar)H), 130.4, 130.5, 130.9, 137.5 and 146.1 (10 × C_q(Ar)); IR (KBr): $\tilde{\nu}$ = 3389 (w, br; OH), 2945 (s; CH), 2856 (m; CH), 1580 (w; ArCC), 1506 (w; ArCC), 1471 (w), 1447 (w), 1432 (w), 1382 (w), 1225 (s), 1023 cm^{-1} (s); MS (FAB +, NOBA matrix): *m/z* (%): 588 (100) $[M+Na]^+$, 566 (41) $[M+H]^+$, 483 (10), 330 (13), 309 (15), 291 (18), 135 (47); HRMS: calcd for $C_{36}H_{41}NO_4P$: 582.2773; found: 582.2768 $[M+NH_4]^+$.

A round-bottomed flask (25 mL) fitted with a short path distillation unit was charged with a solution of acid **38** (0.285 g, 0.50 mmol) in PhCl (15 mL). $[Rh_2(OAc)_4]$ (37 mg, 0.08 mmol) was added and the solution was heated under reflux. The solvent was slowly distilled from the reaction mixture and further portions of PhCl (~6 mL) were added when an equal volume had been removed. After 5 h, the reaction mixture was concentrated under reduced pressure and the residue was purified by column chromatography (light petroleum/CH_2Cl_2 6:5 → CH_2Cl_2) to give a green solid which was suspended in MeOH (5 mL), filtered and air dried to give catalyst **39** as a green powder (0.165 g, 80%). M.p. >330 °C; $[\alpha]_D^{20} = +111.7$ (c = 0.6 in CHCl3); ^{1}H NMR (400 MHz, $CDCl_3$, 25 °C): δ = 1.15 (s, 24H; 8 × CH_3), 1.54–1.72 (m, 48H; 8 × $ArCH_2CH_aH_b$, 8 × $ArCHCH_aH_b$, 8 × $ArCHCH_2CH_2$, 8 × $ArCHCH_2CH_2CH_2$), 1.82–1.89 (m, 8H; 8 × $ArCH_2CH_aH_b$), 2.25–2.29 (m, 8H; 8 × $ArCHCH_aH_b$), 2.77–2.80 (m, 8H; 8 × ArCH), 3.02–3.19 (m, 16H; 8 × $ArCH_2$), 7.10 (d, ^3J(H,H) = 8.8 Hz, 8H),

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7.33 (d, ^3J(H,H) = 9 Hz, 8H), 7.58 (d, ^3J(H,H) = 9 Hz, 8H), 8.04 (d, ^3J(H,H) = 9.5 Hz, 8H); ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C): δ = 26.2 (8 × CH_3), 22.8, 23.2, 31.7, 35.4, 40.4 (40 × CH_2), 39.3 (8 × C_q), 50.4 (8 × CH), 120.9 (8 × *C*(Ar)H), 122.3 (8 × C_q(Ar)), 125.2, 125.9, 128.9 (24 × *C*(Ar)H), 130.3, 130.4, 131.0, 137.0, 147.1 (40 × C_q(Ar)); ^{31}P NMR (200 MHz, $CDCl_3$, 25 °C): δ = 20.9 ; IR (KBr): $\tilde{\nu}$ = 2949 (m, CH), 2865 (w, CH), 1474 (w), 1451 (w), 1387 cm^{-1} (w); MS (FAB +, NOBA matrix): *m/z* (%): 2460 (26) [*M*]$^+$, 1896 (27), 1328 (73), 588 (97), 521 (100).

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[1] a) K. V. Gothelf, K. A. Jorgensen, *Chem. Rev.* **1998**, *98*, 863–909; b) S. Karlsson, H. E. Hogberg, *Org. Prep. Proced. Int.* **2001**, *33*, 105–172.
[2] A. Padwa, S. F. Hornbuckle, *Chem. Rev.* **1991**, *91*, 263–309.
[3] M. P. Doyle, M. A. McKervey, T. Ye, *Modern Catalytic Methods for Organic Synthesis with Diazo Compounds*, Wiley-Interscience, New York, **1998**.
[4] a) A. Padwa, M. D. Weingarten, *Chem. Rev.* **1996**, *96*, 223–269; b) A. Padwa, *Top. Curr. Chem.* **1997**, *189*, 121–158; c) F. Zaragoza-Dörwald, *Metal Carbenes in Organic Synthesis*, Wiley-VCH, Weinheim, **1999**, pp. 206–213.
[5] a) M. P. Doyle in *Catalytic Asymmetric Synthesis*, 2nd ed. (Ed.: I. Ojima), VCH, New York, **2000**, pp. 191–228; b) M. P. Doyle, D. C. Forbes in *Chemistry for the 21st Century: Transition Metal Catalyzed Reactions* (Eds.: S. G. Davies, S. Murahashi), Blackwell Science, Oxford, **1999**, pp. 289–301; c) K. M. Lydon, M. A. McKervery in *Comprehensive Asymmetric Catalysis*, *Vol. II* (Eds.: E. N. Jacobsen, A. Pfaltz, H. Yamamoto), Springer, Berlin, **1999**, pp. 539–580; d) A. B. Charette, H. Lebel in *Comprehensive Asymmetric Catalysis*, *Vol. II* (Eds.: E. N. Jacobsen, A. Pfaltz, H. Yamamoto), Springer, Berlin, **1999**, pp. 581–603; e) M. P. Doyle, M. A. McKervey, *Chem. Commun.* **1997**, 983–989; f) M. A. Calter, *Curr. Org. Chem.* **1997**, *1*, 37–70.
[6] A. Padwa, D. J. Austin, S. F. Hornbuckle, *J. Org. Chem.* **1996**, *61*, 63–72.
[7] D. M. Hodgson, F. Y. T. M. Pierard, P. A. Stupple, *Chem. Soc. Rev.* **2001**, *30*, 50–61.
[8] a) D. M. Hodgson, P. A. Stupple, C. Johnstone, *Tetrahedron Lett.* **1997**, *38*, 6471–6472; b) D. M. Hodgson, P. A. Stupple, C. Johnstone, *Chem. Commun*. **1999**, 2185–2186.
[9] A. Padwa, S. F. Hornbuckle, G. E. Fryxell, Z. J. Zhang, *J. Org. Chem.* **1992**, *57*, 5747–5757.
[10] A. Padwa, S. F. Hornbuckle, G. E. Fryxell, P. D. Stull, *J. Org. Chem.* **1989**, *54*, 817–824.
[11] M. A. Tschantz, L. E. Burgess, A. I. Meyers, *Org. Synth*. **1998**, *Coll. Vol. IX*, 530–533.
[12] D. W. Brooks, L. D.-L. Lu, S. Masamune, *Angew. Chem.* **1979**, *91*, 76–78; *Angew. Chem. Int. Ed. Engl.* **1979**, *18*, 72–73.
[13] M. Ghosh, M. J. Miller, *Tetrahedron* **1996**, *52*, 4225–4238.
[14] M. P. Doyle, C. S. Peterson, D. L. Parker, Jr., *Angew. Chem.* **1996**, *108*, 1439–1440; *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 1334–1336.
[15] M. P. Doyle, D. C. Forbes, M. M. Vasbinder, C. S. Peterson, *J. Am. Chem. Soc.* **1998**, *120*, 7653–7654.
[16] M. P. Doyle, *Aldrichimica Acta* **1996**, *29*, 3–11.
[17] a) M. P. Doyle, S. B. Davies, W. Hu, *Org. Lett.* **2000**, *2*, 1145–7; b) M. P. Doyle, Q.-L. Zhou, S. H. Simonsen, V. Lynch, *Synlett* **1996**, 697–698.
[18] M. P. Doyle, W. Hu, I. M. Phillips, C. J. Moody, A. G. Pepper, A. G. Z. Slawin, *Adv. Synth. Catal.* **2001**, *343*, 112–117.
[19] P. A. Agaskar, F. A. Cotton, L. R. Falvello, S. Han, *J. Am. Chem. Soc.* **1986**, *108*, 1214–1223.
[20] a) A. Padwa, D. J. Austin, *Angew. Chem.* **1994**, *106*, 1881–1899; *Angew. Chem. Int. Ed. Engl.* **1994**, *33*, 1797–1815; b) M. P. Doyle, T. Ren, *Prog. Inorg. Chem.* **2001**, *49*, 113–168.
[21] C. Fernandez-Garcia, M. A. McKervey, T. Ye, *Chem. Commun.* **1996**, 1465–1466.
[22] R. T. Buck, M. P. Doyle, M. J. Drysdale, L. Ferris, D. C. Forbes, D. Haigh, C. J. Moody, N. D. Pearson, Q.-L. Zhou, *Tetrahedron Lett.* **1996**, *37*, 7631–7634.
[23] S. Hashimoto, N. Watanabe, S. Ikegami, *Tetrahedron Lett.* **1990**, *31*, 5173–5174.
[24] M. Anada, O. Mita, H. Watanabe, S. Kitagaki, S. Hashimoto, *Synlett* **1999**, 1775–1777, and references therein.
[25] M. Kennedy, M. A. McKervey, A. R. Maguire, G. H. P. Roos, *J. Chem. Soc. Chem. Commun.* **1990**, 361–362.
[26] a) H. M. L. Davies, P. R. Bruzinski, D. H. Lake, N. Kong, M. J. Fall, *J. Am. Chem. Soc.* **1996**, *118*, 6897–6907; b) H. M. L. Davies, *Eur. J. Org. Chem.* **1999**, 2459–2469.
[27] T. Ye, C. Fernandez-Garcia, M. A. McKervey, *J. Chem. Soc. Perkin Trans. 1* **1995**, 1373–1379.
[28] S. K. Bertilsson, P. G. Andersson, *J. Organomet. Chem.* **2000**, *603*, 13–17.
[29] H. M. L. Davies, N. Kong, *Tetrahedron Lett.* **1997**, *38*, 4203–4206.
[30] H. M. L. Davies, S. A. Panaro, *Tetrahedron Lett.* **1999**, *40*, 5287–5290.
[31] Crystallographic data (excluding structure factors) for the structure reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-1821422 (**22**). Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (fax: (+44) 1223-336-033; e-mail: deposit@ccdc.cam.ac.uk). See also Supporting Information.
[32] M. P. Doyle, D. C. Forbes, *Chem. Rev.* **1998**, *98*, 911–935.
[33] H. Suga, H. Ishida, T. Ibata, *Tetrahedron Lett.* **1998**, *39*, 3165–3166.
[34] a) S. Kitagaki, A. Masahiro, O. Kataoka, K. Matsuno, C. Umeda, N. Watanabe, S. Hashimoto, *J. Am. Chem. Soc.* **1999**, *121*, 1417–1418; b) S. Kitagaki, M. Yasugahira, M. Anada, M. Nakajima, S. Hashimoto, *Tetrahedron Lett.* **2000**, *41*, 5931–5935.
[35] A. Padwa, Y. S. Kulkarni, Z. Zhang, *J. Org. Chem.* **1990**, *55*, 4144–4153.
[36] M. C. Pirrung, J. Zhang, *Tetrahedron Lett.* **1992**, *33*, 5987–5990.
[37] N. McCarthy, M. A. McKervey, T. Ye, M. McCann, E. Murphy, M. P. Doyle, *Tetrahedron Lett.* **1992**, *33*, 5983–5986.
[38] a) P. Müller, C. Baud, Y. Jacquier, M. Moran, I. Nägeli, *J. Phys. Org. Chem.* **1996**, *9*, 341–347; b) P. Müller, C. Baud, Y. Jacquier, *Tetrahedron* **1996**, *52*, 1543–1548; c) P. Müller, D. Fernandez, P. Nury, J.-C. Rossier, *Helv. Chim. Acta* **1999**, *82*, 935–945; d) P. Müller, S. Tohill, *Tetrahedron* **2000**, *56*, 1725–1731.
[39] a) I. Nägeli, Ph.D. Thesis, University of Geneva, **1998**; b) P. Müller, E. Maître jean, *Collect. Czech. Chem. Commun.* **1999**, *64*, 1807.
[40] a) D. J. Cram, R. C. Helgeson, S. C. Peacock, L. J. Kaplan, L. A. Domeier, P. Moreau, K. Koga, J. M. Mayer, Y. Chao, M. G. Siegel, D. H. Hoffman, G. D. Y. Sogah, *J. Org. Chem.* **1978**, *43*, 1930–1946; b) S. S. Peacock, D. M. Walba, F. C. A. Gaeta, R. C. Helgeson, D. J. Cram, *J. Am. Chem. Soc.* **1980**, *102*, 2043–2052.
[41] a) H. Sasai, T. Tokunaga, S. Watanabe, T. Suzuki, N. Itoh and M. Shibasaki, *J. Org. Chem.* **1995**, *60*, 7388–7389; b) M. Terada, Y. Motoyama and K. Mikami, *Tetrahedron Lett.* **1994**, *35*, 6693–6696; c) C. Qian, T. Huang, C. Zhu, J. Sun, *J. Chem. Soc. Perkin Trans. 1* **1998**, 2097–2103.
[42] R. Viterbo, J. Jacques (Richardson-Merrell), US 3848030, **1974** [*Chem. Abstr.* **1973**, *78*, 43129b].
[43] T. Hamada, T. Fukuda, H. Imanishi, T. Katsuki, *Tetrahedron* **1996**, *52*, 515–530.

[44] B. J. Brisdon, R. England, K. Reza, M. Sainsbury, *Tetrahedron* **1993**, *49*, 1103 – 1114.
[45] G. A. Olah, S. C. Narang, B. G. B. Gupta, R. Malhotra, *J. Org. Chem.* **1979**, *44*, 1247 – 1251.
[46] H. J. Callot, F. Metz, *Tetrahedron* **1985**, *41*, 4495 – 4501.
[47] a) V. Enev, C. L. J. Ewers, M. Harre, K. Nickisch, J. T. Mohr, *J. Org. Chem.* **1997**, *62*, 7092 – 7093; b) V. S. Enev, J. Mohr, M. Harre, K. Nickisch, *Tetrahedron: Asymmetry* **1998**, *9*, 2693 – 2699; c) C. Bolm, O. A. G. Dabard, *Synlett* **1999**, 360 – 362; d) V. S. Enev, M. Harre, K. Nickisch, M. Schneider, J. Mohr, *Tetrahedron: Asymmetry* **2000**, *11*, 1767 – 1779; e) K. Kostova, M. Genov, I. Philipova, V. Dimitrov, *Tetrahedron: Asymmetry* **2000**, *11*, 3253 – 3256.
[48] a) A. Togni, S. D. Pastor, *Chirality* **1991**, *3*, 331 – 340; b) K. Muñiz, C. Bolm, *Chem. Eur. J.* **2000**, *6*, 2309 – 2316.
[49] A. Padwa, J. P. Snyder, E. A. Curtis, S. M. Sheehan, K. J. Worsencroft, C. O. Kappe, *J. Am. Chem. Soc.* **2000**, *122*, 8155 – 8167.
[50] D. M. Hodgson, M. Petroliagi, *Tetrahedron: Asymmetry* **2001**, *12*, 877 – 881.
[51] A. Padwa, N. Kamigata, *J. Am. Chem. Soc.* **1977**, *99*, 1871 – 1880.
[52] L. F. Fieser, M. Fieser, *Reagents in Organic Syntheses*, *Vol. 1*, Wiley-Interscience, New York, **1967**, pp. 142 – 143.
[53] J. S. Baum., D. A. Shook, H. M. L Davies, H. D. Smith, *Synth. Commun.* **1987**, *17*, 1709 – 1716.
[54] H. M. L. Davies, T. Hansen, M. R. Churchill, *J. Am. Chem. Soc.* **2000**, *122*, 3063 – 3070.
[55] V. Teetz, R. Geiger, H. Gaul, *Tetrahedron Lett.* **1984**, *25*, 4479 – 4482.
[56] G. H. P. Roos, M. A. McKervey, *Synth. Commun.* **1992**, *22*, 1751 – 1756.

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