An Application of Electronic Asymmetry to Highly Enantioselective Catalytic Diels−Alder Reactions

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Abstract: The compounds (R_{Ru})-[CyRuCl(*S*)-BINPO]SbF_6 and [CyRuCl(*S*)-TolBINPO]SbF_6 (Cy = η^6-cymene), were synthesized from $(CyRuCl_2)_2$ and the appropriate non-C_2-symmetric bisphosphine monoxide ligands (*S*)-BINPO and (*S*)-TolBINPO (BINPO = 2,2′-bis(diphenylphosphino)-1,1′-binaphthyl) in the presence of $NaSbF_6$. When these complexes were mixed with $AgSbF_6$ the resulting Lewis acids catalyzed the Diels−Alder cycloaddition of cyclopentadiene and methacrolein. The product (2*S*)-methylbicyclo[2.2.1]hept-5-ene-2-carboxaldehyde was obtained with excellent diastereoselectivity (up to 99%) and enantioselectivity (up to 99%) in several cases. When the complexes containing the analogous C_2-symmetric bisphosphine ligands (*S*)-BINAP and (*S*)-TolBINAP were employed as catalysts, the Diels−Alder cycloadducts were obtained with much lower enantioselectivity (19 to 50%) for the opposite antipode. Although some of the effect may arise from chelate ring size change, much of the enhanced stereoselectivity of (R_{Ru})-[CyRuCl(*S*)-BINPO]SbF_6 and [CyRuCl(*S*)-TolBINPO]SbF_6 can be attributed to the electronic asymmetry at the stereogenic Ru center.

Introduction

The implementation of enantiopure organometallic catalysts is an increasingly versatile methodology in asymmetric organic synthesis.[1] Typically, bidentate C_2-symmetric enantiopure ligand sets are employed as auxiliaries to the metal center to control the stereochemical assembly of an organic substrate at the catalyst site. In many instances, optimum stereoselectivity for a particular asymmetric event is realized when using ligands of C_2-symmetry because the number of diastereomeric transition states during the stereodetermining step is reduced, relative to ligands of lower symmetry.[2] However, an alternative approach relies on the employment of non-C_2-symmetric heterobidentate enantiopure ligands which engender electronic asymmetry at the metal center.[3] Perturbation of the metal electronic character can generate a superior chiral site in cases where catalytic intermediates do not inherently possess symmetry similar to that of the chiral ligand.[4] For these situations, the selective binding and orientation of an organic substrate prior to a stereoselective procedure facilitates manipulation of the catalytic event with greater stereocontrol.

We have successfully used unsymmetrical transition metal complexes containing stereogenic metal centers as stoichiometric reagents to functionalize prochiral organic molecules enantioselectively.[5] The source of enantioselectivity was attributed to the preferential orientation of the metal-bound organic precursor that was determined by the different bonding properties of the ligands initially attached to the metal. Electronic effects have also been observed in catalytic systems, such as the hydroformylation of olefins with Rh-based catalysts, for which C_1-symmetric ligands containing mixed bisphosphines have been shown to influence linear:branched regioselectivity.[6] Also, Achiwa demonstrated how catalyst activity and enantioselectivity were modulated by the choice of phosphine aryl substituents in mixed bisphosphine systems.[7] Electronic asymmetry has been proposed to account for the improved enantioselectivity in numerous metal-catalyzed organic transformations, including olefin epoxidation,[8] the hydrocyanation of vinyl arenes,[9] olefin hydroformylation,[10] aldol reactions,[11] and the hydrogenation of dehydroaminoesters and itaconate esters.[12] We have recently investigated the synthesis of bisphosphine monoxide complexes of Ru and Os where the metal center is chiral.[3,13] Included in this series was the compound (R_{Ru})-[CyRuCl(*S*)-BINPO]SbF_6 [**1**; Cy = cymene, BINPO = (2-diphenylphosphino,2′-diphenylphosphineoxide)-binaphthyl] which was confirmed to be an active in situ Lewis acid cocatalyst for the Diels−Alder reaction of methacrolein and cyclopentadiene with moderate enantioselectivity. Recently, several compounds containing stereogenic metal centers have been identified as Diels−Alder catalysts, although the degree of enantioselectivity

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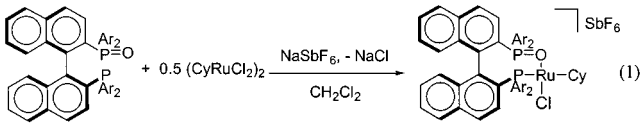
has not yet reached acceptable levels.[14] Reported here is our preliminary study on optimizing the cycloaddition reaction of cyclopentadiene to α,β-enals with remarkably high (99%) enantioselectivity with **1** as a catalyst precursor. Identical catalytic assays with the C_2-symmetric ligand equivalent, (*S*)-BINAP, resulted in much poorer enantioselectivities, thus providing an, as yet, rare instance where a transition metal catalyst relying on the principles of electronic asymmetry effectively promoted more stereoselective Diels−Alder reactions.

Results and Discussion

The bisphosphine monoxide ligands (*S*)-BINPO and (*S*)-TolBINPO [TolBINPO = (2-di(*p*-tolyl)phosphino, 2′-di(*p*-tolyl)-phosphineoxide)-binaphthyl] were synthesized according to the method described by Grushin.[15] In a procedure modified from the original preparation for **1**, the complexes (R_{Ru})-[CyRuCl-(*S*)-BINPO]SbF_6 (**1**) and [CyRuCl(*S*)-TolBINPO]SbF_6 (**2**) were more conveniently produced from the corresponding ligands, $(CyRuCl_2)_2$ and $NaSbF_6$ in CH_2Cl_2 as shown in eq 1.[13b] Isolated



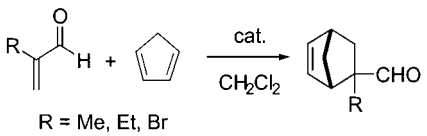
1 Ar = Phenyl
2 Ar = p-Tolyl

as analytically pure red solids in excellent yield (85%, **1**; 88%, **2**), characterization by ^1H, $^{13}C\{^1H\}$, and $^{31}P\{^1H\}$NMR spectroscopy revealed that **1** was obtained as a single diastereomer (R_{Ru}, *S*), as established by X-ray crystallography, whereas **2** contained a 10:1 mixture of diastereomers, presumably with (R_{Ru}, *S*) as the major component.[3b]

Compounds **1** and **2** were then investigated as Lewis acid catalysts for the cycloaddition of CpH (CpH = cyclopentadiene) to several α-substituted α,β-enals given the application of some bicyclo[2.2.1]hept-5-ene-2-carboxaldehydes to prostaglandin synthesis.[16] When a slight excess of **1** (1.1 equiv) was mixed with $AgSbF_6$, the resulting complex, **3**, was activated toward Lewis acid catalysis. ^1H and $^{31}P\{^1H\}$ NMR spectroscopy revealed that the resting state of the catalyst complex was the diastereopure aqua adduct [CyRu(OH_2)(*S*)-BINPO]$(SbF_6)_2$ (**3**). The aqua complex forms from trace water in the solvent and exposure of reactants to the atmosphere.[17] The reaction is relatively insensitive to trace water and the use of careful inert atmosphere technique is neither required nor does it have a significant effect on selectivities. Small amounts of the chloride precursor, **1**, were also detected owing to the ratio of [Ag]:[**1**]. This ratio was chosen to avoid the presence of silver ion which could act as a nonselective catalyst. At −24 °C, a mixture of methacrolein and cyclopentadiene (10 equiv) was cleanly converted to 2-methylbicyclo[2.2.1]hept-5-ene-2-carboxaldehyde (**4**) with excellent enantioselectivity (94%) for (2*S*)-**4** and *exo* diastereoselectivity (99%) by using a 10 mol % catalyst loading of **1** (11 mol %) and $AgSbF_6$ (10 mol %) (Table 1).[18] Cooling the reaction mixture to −78 °C provided **4** with an enhanced enantioselectivity of 99% for (2*S*)-**4** under otherwise identical conditions. As shown in Table 1, when the catalyst loading was decreased to 1 mol %, there was a noticeable drop in enantioselectivity at −24 °C, although at −78 °C the product **4** was still obtained with satisfactory enantiopurity. ^1H NMR experiments indicated that the reaction was complete after 2 h with 10 mol % catalyst; however, the reaction time was extended to 12 h at a 1 mol % loading to ensure 100% conversion of methacrolein. When performed on a more preparative scale, **4** could be isolated after 100% conversion as a white solid in 84% yield after workup (Table 1). As shown in Table 1, the cycloadduct 2-ethylbicyclo[2.2.1]hept-5-ene-2-carboxaldehyde (**5**) was also prepared from 2-ethylpropenal and CpH with excellent enantioselectivity (95%) and *exo* diastereoselectivity (99%) under identical catalytic conditions. Experiments with the dienophile α-bromoacrolein and cyclopentadiene afforded the corresponding product 2-bromobicyclo[2.2.1]hept-5-ene-2-carboxaldehyde (**6**) with reduced stereoselectivity (76%, Table 1), albeit with complete conversion and satisfactory diastereoselectivity. Kündig has developed a bisphosphinite Ru assembly that catalytically produced *exo*-**6** with excellent enantioselectivity when the basic additive 2,6-lutidine was included.[19] With catalyst **3**, the inclusion of 2,6-lutidine in the reaction mixture resulted in catalyst deactivation. Notably, in all experiments with **3**, product work up required precipitation of the catalyst residue from pentane as an orange solid that could then be isolated by filtration. Spectroscopic examination of the postreaction catalyst species indicated that the aquo complex, **3**, was regenerated after the catalytic event, available to be recycled for further experiments.[20]

When the compound [CyRuCl(*S*)-TolBINPO](SbF_6) (**2**) was employed as the Lewis acid precatalyst for the Diels−Alder

Table 1. Diels−Alder Reactions of CpH Catalyzed by [CyRu(*S*)-BINPO]$(SbF_6)_2$



R = Me, Et, Br

entry (R)	catalyst[a] loading (%)	temp (°C)	product	conversion (%)	de (%)	ee (%) [config]
1 (Me)	10	-78	**4**	100	93	99 [*S*-(+)]
2 (Me)	1	-78	**4**	100	91	92 [*S*-(+)]
3 (Me)	10	-24	**4**	100	99	94 [S−(+)]
4 (Me)	1	-24	**4**	100	95	85 [*S*-(+)]
5 (Me)[b]	10	-78	**4**	5		3 [*S*-(+)]
6 (Et)	10	-78	**5**	100	99	95
7 (Et)	10	-24	**5**	100	99	93
8 (Br)	10	-78	**6**	100	96	76
9 (Br)	10	-24	**6**	100	88	50

[a] All reactions except 5 were conducted in CH_2Cl_2 with the in situ Lewis acid generated from [CyRuCl(*S*)-BINPO]SbF_6 (11 mol %) and $AgSbF_6$ (10 mol %). [b] Assay conducted in the presence of 10 mol % 2,6-lutidine.

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(17) Aqua complexes are frequently observed in nonpolar solvents of organometallic Lewis acids.[14b,c] Some specific examples are given in the following. (a) Cp*Rh: Carmona, D.; Cativiela, C.; Garcia-Correas, R.; Lahoz, F. J.; Lamata, M. P.; Lopez, J. A.; Viu, M. P. L.-R.; Oro, L. A.; Jose, E. S.; Viguri, F. *J. Chem. Soc., Chem. Commun.* **1996**, 1247. (b) Tp-(*i*-Pr)Ru: Takahashi, Y.; Akita, M.; Hikichi, S.; Moro-oka, Y. *Inorg. Chem.* **1998**, *37*, 3186. (c) Tp(*i*-Pr)Ru: Takahashi, Y.; Hikichi, S.; Akita, M.; Moro-oka, Y. *Chem. Commun.* **1999**, 1491. (d) (PAN)Ru: Therrien, B.; Ward, T. R. *Angew. Chem., Int. Ed.* **1999**, *38*, 405.

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(20) $^{31}P\{^1H\}$ NMR (CD_2Cl_3, 298 K) δ 66.4 (s, P[V]), δ 52.2 (s, P[III]).

Table 2. Diels−Alder Reactions of CpH Catalyzed by [CyRu(*S*)-TolBINPO](SbF$_6$)$_2$

entry (R)	catalyst[a,b] loading (%)	temp. (°C)	product	conversion (%)	de (%)	ee (%) [config]
1 (Me)	10	−78	**4**	15	96	98 [*S*-(+)]
2 (Me)	10	−24	**4**	100	98	93 [*S*-(+)]
3 (Et)	10	−78	**5**	10	99	91
4 (Et)	10	−24	**5**	100	99	93
5 (Br)	10	−78	**6**	6		
6 (Br)	10	−24	**6**	86	68	10

[a] All reactions were conducted in CH_2Cl_2 with the in situ Lewis acid generated from [CyRuCl-(*S*)-TolBINPO]SbF$_6$ (11 mol %) and AgSbF$_6$ (10 mol %). [b] The [CyRuCl-(*S*)-TolBINPO]SbF$_6$ contained a 10:1 mixture of diastereomers, but this does not reflect the diastereomeric composition of the catalytic species.

reaction of the α-alkyl α,*β*-enals and CpH, excellent product selectivites were maintained (Table 2). Although a reaction temperature of −24 °C afforded the cycloadducts **4** (98% de, (*S*)-93% ee) and **5** (99% de, 93% ee) with 100% conversion, the substrate conversion was considerably reduced at − 78 °C. Slower conversion rates to **4** and **5** (10−15%) were observed with the catalyst derived from **2** at low temperatures because of the inductive effect of the *p*-tolyl aryl groups. Electron donation to the Ru center moderated its Lewis acidity and catalytic activity, although **4** and **5** were still obtained with high optical yield (Table 2) indicating that the stereodifferentiation of the chiral catalyst remained effective. The modified catalyst, **2**, in fact proved to be a poor catalyst candidate for the synthesis of the bromo analogue, **6**, in all regards. The pronounced sensitivity of the ruthenium center's Lewis acidity to the substitution pattern of the peripheral phosphino aryl substituents shown here suggested that Lewis acidity can be predictably manipulated. Presumably, catalytic activation of otherwise inert organic substrates could be attained by appending phosphines containing electron-deficient groups to the Lewis acid center.[19]

It was proposed that **1** and **2** were found to be effective catalysts for the enantioselective synthesis of the bicyclic moieties **4**−**6** by virtue of the stereogenic metal center. The importance of electronic asymmetry to the degree of catalytic asymmetric induction was then evaluated by investigation of the cations produced by abstracting the halides from [CyRuCl-(*S*)-BINAP]Cl (**7**) and [CyRuCl(*S*)-TolBINAP]Cl (**8**) as Diels−Alder Lewis acid catalysts. In these instances, the Ru center was not stereogenic and chiral induction during the catalytic event relied on the influence of the C_2-symmetric chiral auxiliaries (*S*)-BINAP and (*S*)-TolBINAP. Precatalysts **7** and **8** were prepared according to literature protocols and catalytically activated upon addition of 1.9 equiv of AgSbF$_6$.[21] Each catalyst candidate was then screened and successfully promoted the cycloaddition of methacrolein and CpH to **4** under conditions identical to those previously described for the bisphosphine monoxide analogues. As shown in Table 3, both **7** and **8** displayed moderate enantioselectivity (19−50%) at best for the *opposite* antipode (*R*)-**4**, when compared to the superior performance of the bisphosphine monoxide congeners (93−99% (*S*)-**4**). Although some of the difference may arise from chelate ring size effects, this stark contrast in reactivity clearly indicated that the excellent catalytic stereoselectivity noted for **1** and **2** can be attributed to the use of the bisphosphine monoxide ligands to generate an electronically asymmetric stereogenic Lewis acidic Ru center.

The sense of stereochemical induction observed when using catalysts derived from **1** and **2** can be best understood when considering the two possible *anti-s-trans* conformations in the η^1-bound Ru-methacrolein intermediate. The preferential orbital

Table 3. [CyRu(*S*)-BINAP](SbF$_6$)$_2$ and [CyRu(*S*)-TolBINAP](SbF$_6$)$_2$ Lewis Acid Catalyzed Reaction of CpH and Methacrolein

entry (ligand)[a]	temp (°C)	product	conversion (%)	de (%)	ee (%) [config]
1 (BINAP)	−24	**4**	100	93	50 [*R*-(−)]
2 (BINAP)	−78	**4**	100	82	19 [*R*-(−)]
3 (TolBINAP)	−24	**4**	19	99	26 [*R*-(−)]
4 (TolBINAP)	−78	**4**	15	99	24 [*R*-(−)]

[a] All reactions were conducted in CH_2Cl_2 with the in situ Lewis acid generated from the cymeneruthenium dichloride complex (11 mol %) and AgSbF$_6$ (20 mol %).

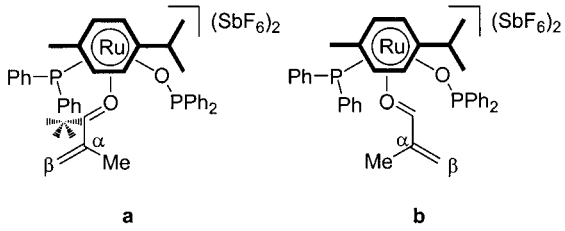

Figure 1. Sterically encumbered (**a**) and stable (**b**) conformations of a Ru-methacrolein intermediate.

interactions of stereogenic Ru centers with η^1-coordinated carbonyl π-systems have been previously shown to align aldehyde ligands in the solid and solution state.[22] The differential bonding of the d orbitals aligned along the Ru−P and Ru−O bonds with the carbonyl π and π^* orbitals of the bound aldehyde confines the enal to two orientations. That is, the P−Ru−O═C dihedral angle is restricted to two values (∼0 and 180°). Steric interactions then determine which of these two conformations will be the most stable. As shown in Figure 1, conformation **a** arranges the bulk of the methacrolein ligand toward the PPh$_2$ functional group, generating significant steric hindrance between those two moieties. Alternatively, conformer **b** orients the methacrolein ligand toward the cavity created by the Ph$_2$P═O group of the bisphosphine monoxide ligand where there is considerably less steric hindrance with the remote arylphosphino groups. It is likely, therefore, that **b** is the actual conformation adopted in solution given the ability of the sterically modest P═O group to accommodate the methacrolein ligand. Fixed in this key conformational state, the trajectory of a reagent toward the methacrolein C$_\alpha$ *Re*-diastereoface would be blocked by the binaphthyl and aryl rings, whereas the C$_\alpha$ *Si*-diastereoface would remain exposed. The culmination of these effects organizes a well-defined catalyst−substrate structure that facilitates a controlled approach of CpH to the methacrolein C$_\alpha$ *Si*-diastereoface giving the (*S*)-**4** enantiomer (Figure 2). For the simpler bisphosphine analogues, **7** and **8**, this implies that the interface between chiral catalyst and prochiral substrate is less well-defined in terms of both conformational selectivity and alignment of the η^1-bound aldehyde. This ultimately leads to poorer enantioselectivity, as observed experimentally.

In conclusion, we have developed some novel chiral Lewis acid complexes as effective catalysts for enantioselective Diels−Alder reactions. The electronic asymmetry associated with the stereogenic Ru center was found to be a critical factor in catalyst stereorecognition. Future work will be concerned with expanding

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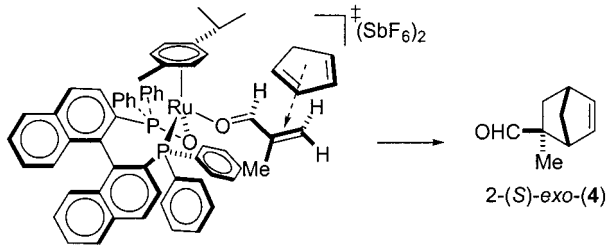

Figure 2. Proposed trajectory of CpH during reaction with [CyRu(*S*)-BINPO-OCHCMeCH$_2$](SbF$_6$)$_2$ to give 2-(*S*)-*exo*-(**4**). The binaphthyl and aryl rings block the methacrolein C$_\alpha$ *Re*-diastereoface, leaving the exposed *Si*-face open to attack from CpH.

the scope of asymmetric organic reactions with such catalysts to cases where conventional C_2-symmetric catalysts fail to provide products with satisfactory enantiomeric purity.

Experimental Section

The reactions were carried out by using standard inert atmosphere techniques where necessary. The solvent CH_2Cl_2 and pentane were distilled from CaH_2 prior to use and degassed by 2 freeze−pump−thaw cycles where necessary. The compounds $NaSbF_6$ (Strem), methacrolein, 2-ethylpropenal, $AgSbF_6$, and reagent grade Et_2O (Aldrich) were used without purification. Cyclopentadiene was cracked from dicyclopentadiene (Aldrich) prior to use; bromoacrolein[16] and $(CyRuCl_2)_2$[23] were prepared according to literature procedures. The compounds (*S*)-BINPO and (*S*)-TolBINPO were prepared from (*S*)-BINAP and (*S*)-TolBINAP (Strem), respectively, based on the literature procedures.[15] The ^{1}H, ^{31}P{^{1}H}, and ^{13}C{^{1}H} NMR spectra were recorded on a Bruker 400 or 500 MHz spectrometer at 25 °C unless stated otherwise. The chiral shift experiments to determine product ee were determined with use of Eu(hfc)$_3$ (Aldrich).

Synthesis of [CyRuCl(*S*)-BINPO]SbF$_6$ (1). A Schlenk tube was charged with $(CyRuCl_2)_2$ (0.32 g, 0.52 mmol), $NaSbF_6$ (0.27 g, 1.00 mmol), and (*S*)-BINPO (0.70 g, 1.10 mmol). The vessel was evacuated and backfilled with N_2 before immersion in a N_2 bath. An aliquot of CH_2Cl_2 (20 mL) was introduced by syringe giving a pale orange matrix that was degassed by 2 freeze−pump−thaw cycles. The reaction mixture was allowed to warm to ambient temperature and stirred for 4 h. The dark red solution was filtered through Celite, washing the Celite cake with CH_2Cl_2 (20 mL) until colorless. The resultant red solution was concentrated (3 mL) and layered with Et_2O (20 mL). On standing, a red precipitate was isolated by syringe filtration of the remaining orange solution. The sample was dried in vacuo to give [CyRuCl(*S*)-BINPO]SbF$_6$ as a dark red powder (1.21 g, 85% yield). ^{31}P{^{1}H} NMR ($CDCl_3$, 298 K, 162 MHz): δ 53.0 (s, P[V]), 45.3 (s, P[III]). ^{1}H NMR ($CDCl_3$, 298 K, 400 MHz): δ 8.06−6.58 (m, 30 H, Ar-*H*), 6.54 (d, J = 8.7 Hz, 1 H, Ar-*H*), 6.13 (d, J = 6.0 Hz, 1 H, Cy-*H*), 5.99 (d, J = 6.2 Hz, 1H, Cy-*H*), 5.68 (d, J = 8.7 Hz, 1 H, Ar-*H*), 5.44 (d, J = 6.2 Hz, 1H, Cy-*H*), 4.58 (d, J = 6.0 Hz, 1 H, Cy-*H*), 2.48 (spt, J = 6.9 Hz, 1 H, Cy C*H*CH$_3$), 1.26 (s, 3 H, Cy C*H*$_3$), 1.15 (d, J = 6.9 Hz, 3 H, Cy CHC*H*$_3$), 0.93 (d, J = 6.9 Hz, 3 H, Cy CHC*H*$_3$).^{13}C{^{1}H} NMR ($CDCl_3$, 298 K, 126 MHz): δ 137.40, 137.31, 134.76, 134.12, 133.38, 133.28, 133.07, 132.64, 131.78, 131.59, 131.32, 130.81, 130.53, 130.44, 130.23, 130.11, 129.97, 129.00, 128.88, 128.70, 128.61, 128.19, 127.73, 127.57, 127.11, 126.85, 126.51, 126.18, 110.96, 100.58, 97.29, 90.73, 84.27, 71.57, 31.27, 22.45, 22.34, 18.19. Anal. Calcd for $C_{54}H_{46}OP_2ClRuSbF_6$: C, 56.64; H, 4.05. Found: C, 56.14; H, 4.34.

Synthesis of [CyRuCl(*S*)-TolBINPO]SbF$_6$ (2). A Schlenk tube was charged with $(CyRuCl_2)_2$ (0.10 g, 0.17 mmol), $NaSbF_6$ (0.09 g, 0.34 mmol), and (*S*)-TolBINPO [0.35 g, 0.50 mmol; ^{31}P{^{1}H} NMR ($CDCl_3$, 298 K, 162 MHz) δ 30 (s, P[V]), −15 (s, P[III])]. The vessel was evacuated and backfilled with N_2 before immersion in a N_2 bath. An aliquot of CH_2Cl_2 (10 mL) was introduced by syringe giving a pale orange matrix that was degassed by 2 freeze−pump−thaw cycles. The reaction mixture was allowed to warm to ambient temperature and stirred for 4 h. The dark red solution was filtered through Celite, with washing of the Celite cake with CH_2Cl_2 (20 mL) until colorless. The resultant red solution was concentrated (2 mL) and layered with Et_2O (20 mL). On standing, a red precipitate was isolated by syringe filtration of the remaining orange solution. The sample was dried in vacuo to give [CyRuCl(*S*)-TolBINPO]SbF$_6$ (10:1 mixture of diastereomers) as a dark red powder (0.36 g, 88% yield). ^{31}P{^{1}H} NMR ($CDCl_3$, 298 K, 162 MHz): major diastereomer δ 53.5 (s, P[V]), 44.1 (s, P[III]); minor diastereomer δ 53.9 (s, P[V]), 44.4 (s, P[III]). ^{1}H NMR ($CDCl_3$, 298 K, 500 MHz): δ 8.02−6.44 (m, 28 H, Ar-*H*), 6.08 (d, J = 6.0 Hz, 1 H, Cy-*H*), 5.90 (d, J = 6.2 Hz, 1H, Cy-*H*), 5.63 (d, J = 8.8 Hz, 1 H, Ar-*H*), 5.37 (d, J = 6.2 Hz, 1H, Cy-*H*), 4.56 (d, J = 6.0 Hz, 1 H, Cy-*H*), 2.56 (s, 3 H, Tol C*H*$_3$), 2.49 (s, 3 H, Tol C*H*$_3$), 2.47 (obs spt, J = 6.9 Hz, 1 H, Cy C*H*CH$_3$), 2.01 (s, 3 H, Tol C*H*$_3$), 1.98 (s, 3 H, Tol C*H*$_3$), 1.30 (s, 3 H, Cy C*H*$_3$), 1.14 (d, J = 6.9 Hz, 3 H, Cy CHC*H*$_3$), 0.93 (d, J = 6.9 Hz, 3 H, Cy CHC*H*$_3$). ^{13}C{^{1}H} NMR ($CDCl_3$, 298 K, 126 MHz): δ 145.11, 142.21, 142.01, 141.27, 141.13, 137.24, 137.17, 134.62−125.99, 110.73, 100.45, 97.04, 90.38, 83.90, 71.69, 31.19, 22.46, 22.26, 22.06, 21.73, 21.52, 21.09, 18.29. Anal. Calcd for $C_{58}H_{54}OP_2ClRuSbF_6$: C, 57.99; H, 4.53. Found: C, 58.58; H, 4.79.

General Catalytic Synthesis of *exo*-2-Methylbicyclo[2.2.1]hept-5-ene-2-carboxaldehyde (4). A vial was charged with methacrolein (0.15 g, 2.1 mmol) and CH_2Cl_2 (1 mL) followed by cooling for 0.5 h at −24 °C. A centrifuge tube was charged with [CyRuCl(*S*)-BINPO]SbF$_6$ (0.031 g, 0.023 mmol) and CH_2Cl_2 (1 mL). A sample of $AgSbF_6$ (0.007 g, 0.021 mmol) was added to the reaction mixture under an N_2 atmosphere and the walls of the tube were washed with CH_2Cl_2 (1 mL). The contents of the flask were mixed and a fine precipitate was obtained after 10 min. The tube was centrifuged to provide a clear red solution and a white precipitate. The catalyst solution was transferred by syringe to the vial containing the methacrolein solution and the reaction mixture was then allowed to cool for 0.5 h. An aliquot of freshly distilled CpH (1.7 g, 21 mmol), which had been precooled at −24 °C for at least 2 h, was then added by syringe to the reaction mixture giving a clear red solution. After 12 h, the solution was transferred to a flask where the solvent was removed under reduced pressure to give an orange residue. The residue was extracted with pentane (2 × 20 mL) and the pentane solution filtered through Celite to provide a clear, colorless solution. The volatiles were removed under reduced pressure to provide the target compound as white glassy solid (0.235 g, 84% yield).

For the reactions carried out with 10 mol % catalyst, the concentration of the catalyst in CH_2Cl_2 was held constant and the same experimental procedure was followed. The amount of the reactants was decreased by a factor of 10. Reaction times were typically 12 h, although ^{1}H NMR spectroscopy indicated that the reaction was over after 2 h. Trace amounts of $(CpH)_2$ were removed by filtration of the product through a silica plug.

Analysis of ee and de. Conversion of acroleins to the corresponding Diels−Alder product was determined by ^{1}H NMR analysis of the crude reaction mixture. The diastereomeric excess (de) was determined by ^{1}H NMR spectroscopy by integration of the exo and endo aldehyde proton resonances. The de provided in Tables 1−3 refers to the excess of the exo diastereomer.

2-Methylbicyclo[2.2.1]hept-5-ene-2-carboxaldehyde (4). ^{1}H NMR ($CDCl_3$, 298 K, 500 MHz): δ 9.69 *exo*-C*H*O (major); δ 9.39 *endo*-C*H*O (minor). The shift reagent Eu(hfc)$_3$ was used to determine the enantioselectivity of the exo diastereomer. It was observed that the signal for the (*S*)-enantiomer was consistently shifted further downfield than the signal for the (*R*)-enantiomer. When [CyRuCl(*S*)-BINPO]SbF$_6$ and [CyRuCl(*S*)-TolBINPO]SbF$_6$ were used as precatalysts, the (*S*)-enantiomer was obtained as the major enantiomer. This was established by comparison of the sign of the optical rotation to the literature values.[18] The enantioselectivity was then determined by line fitting analysis (Peakfit 4.0, Jandel Scientific) of the two signals.

2-Ethylbicyclo[2.2.1]hept-5-ene-2-carboxaldehyde (5). ^{1}H NMR ($CDCl_3$, 298 K, 500 MHz): δ 9.70 *exo*-C*H*O (major); δ 9.40 *endo*-C*H*O (minor). Use of the chiral europium shift reagent failed to distinguish the enantiomers. The enantioselectivity of the exo diastereomer was determined by derivatization with (2*R*,4*R*)-2,4-pentanediol

(23) Bennett, M. A.; Huang, T.-N.; Methson, T. W.; Smith, A. K. *Inorg. Synth.* **1982**, *21*, 75.

to the corresponding diastereomeric acetals. Integration or line fitting analysis (Peakfit 4.0, Jandel Scientific) of the resonances for the C*H*O_2 protons δ 4.85 and 4.82 was used to determine the enantioselectivity. When [CyRuCl(*S*)-BINPO]SbF_6 and [CyRuCl(*S*)-TolBINPO]SbF_6 were used as precatalysts, the signal at δ 4.85 corresponded to the major enantiomer. The configuration of the major enantiomer was not determined, but is presumed to be the same as that found for the major isomer found for methacrolein, i.e., (*S*).

2-Bromobicyclo[2.2.1]hept-5-ene-2-carboxaldehyde (6). ^{1}H NMR ($CDCl_3$, 298 K, 500 MHz): δ 9.55 *exo*-C*H*O (major); δ 9.33 *endo*-C*H*O (minor). The shift reagent Eu(hfc)$_3$ was used to determine the enantioselectivity of the exo diastereomer. When [CyRuCl(*S*)-BINPO]-SbF_6 and [CyRuCl(*S*)-TolBINPO]SbF_6 were used as precatalysts, the major enantiomer of the exo product corresponded to the signal that was shifted furthest downfield by the shift reagent. The enantioselectivity was then determined by line fitting analysis of the two signals. The configuration of the major enantiomer was not determined.

Catalyst Studies of Cations Derived from 7 and 8. [CyRuCl(*S*)-BINAP]Cl (**7**) and [CyRuCl(*S*)-TolBINAP]Cl (**8**) were prepared according to published procedures.[21] A mole ratio of 1.9:1 of $AgSbF_6$ was added to CH_2Cl_2 solutions of **7** and **8** to produce, in situ, the catalytically active species [CyRu(*S*)-BINAP]$(SbF_6)_2$ and [CyRu(*S*)-TolBINAP]$(SbF_6)_2$, respectively. These catalyst solutions (10 mol % loading) were transferred by syringe to cold methacrolein solutions and the catalytic procedure described above was carried out.

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